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September 24, 2018

Mrs. Jean Romback-Bartels
Secretaries Director
Wisconsin Department of Natural Resources
2984 Shawano Avenue
Green Bay, WI 54313

Re: Electric/Water Velocity AIS Deterrent System Proposal to Open the Menasha Lock

Dear Mrs. Romback-Bartels:

The Fox River Navigational System Authority (FRNSA) is presenting the attached proposal for the construction of an electronic/water velocity barrier at the Menasha Lock. The proposed barrier will prevent the round goby and other possible aquatic invasive species (AIS) from migrating upstream into Lake Winnebago.

In the last three years, FRNSA has spent a significant amount of volunteer and staff time as well as financial resources to identify, explore, and evaluate a number of possible alternative proposals that would allow the Menasha Lock to be reopened.

The attached proposal is submitted for Wisconsin DNR approval. We request that the DNR evaluate and respond to the proposal within the next 30 days.

Respectfully,

The Board of Directors of the Fox River Navigational System Authority

S. Timothy Rose
Board Chairman

Jeremy Cords
Chief Executive Officer

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Proposal: Menasha Lock Electric/Water Velocity AIS Deterrent System

Introduction

In September 2015, the round goby was found in Little Lake Butte des Morts (LLBDM). At that time, there were five unrestored locks and three miles of dewatered channel downstream of LLBDM. *The migration of the round goby into LLBDM did not occur through the Fox Lock system. (10, 13)*

Over 150 years ago, private interests began building a canal and lock system connecting the Fox River with the Mississippi River. The Fox River in northeastern Wisconsin was historically a trade and navigation route. The Army Corps of Engineers (ACOE) managed the lock system from 1872 until 1982. In 1982, the ACOE recommended dismantling the lock system. Shortly afterwards, concerned citizens and political leaders began a campaign to fund the lock system and keep it open.

In 2001, the lock system was transferred from the federal government to the State of Wisconsin. In 2002, FRNSA was established by the Wisconsin Legislature to "restore, maintain and operate the Fox River Lock System." FRNSA has completed restoration of all 17 locks. The locks and associated properties are listed on the National Register of Historic Places.

The Menasha lock opened in 1856, rebuilt in 1970, and underwent a major rehab construction in 2014. Lock dimensions are 144 feet long by 35 feet wide with a lift of 9.7 feet.

The round gobies were first found at the west end of Lake Erie in 1990. At that time, concerns were raised that the goby would significantly affect the food chain for other fish. Recently published articles (10, 11, and 12) indicate that the round goby has been incorporated into the food chain of larger fish. High mortality rates suggest that the round goby may be under predatory control in Lake Michigan (16).

The Menasha lock was closed at the request of Wisconsin DNR in September 2015. This closure prevented the spread of round goby (neogobius melanostomus) into the Lake Winnebago system. The closure of the Menasha lock had a significant impact on FRNSA's statutory obligation to "restore, maintain and operate the Fox River lock system" for the benefit of the public. The closure of the lock has also affected the economic development and stability of properties and businesses along the river.

FRNSA's proposed solution:

- is based on sound, accepted scientific information and technology that will protect the environmental integrity of the Lake Winnebago watershed
- will allow the reopening of the Menasha Lock to navigational boat traffic
- will provide an aquatic invasive species (AIS) deterrent system that is flexible and will allow potential modifications in the future

The proposed project will include construction of an electric barrier system that will work in conjunction with a water velocity barrier to prevent round goby and other AIS from migrating into the Lake Winnebago system.

This proposal is a realistic plan based on the current scientific knowledge and technology to restore access to Lake Winnebago and the Fox River through the Menasha lock.

Safety

Smith-Root systems are designed to promote human safety. *More than 65 Smith-Root electric barriers are operational without a single incident of human injury*. (17) For further information, see attached.

Adverse Impact

Despite the efforts that will be made with the electric/water velocity barrier at the Menasha lock, trailered boat access ramps present a significant threat for AIS introductions into the Lake Winnebago watershed. There are more than 60 access points for boats on the Lake Winnebago system. Based on the number of available parking spaces in the launch sites alone, assuming a 30 percent capacity on weekdays and a 60 percent capacity on weekends, more than 23,000 boats will be launched in the Lake Winnebago system. **Unless all boaters take precautions to prevent the spread of AIS from lake to lake via trailered boats, this vector will remain a serious threat to the Lake Winnebago system.** (15) Construction, renovation, and installation of docks and other marine equipment, lake monitoring, and habitat restoration may create other vectors of AIS contamination. Fishing tournaments where boats are trailered from site to site, and float planes with pontoons, are also possible vectors for AIS contamination.

Given the current vectors of possible AIS introduction, the proposed electric/water velocity barrier, would provide greater protection to the Lake Winnebago system than currently exists today. **In summary, introduction of an AIS into the Lake Winnebago water system could occur regardless of the proposed barrier and its use.**

Project Construction

The proposed design and construction of the electric/water velocity barrier does not require any modification of the existing Menasha lock. The barrier will require the construction of 40 feet long and 36 feet wide U-shaped channel with smooth sidewalls downstream from the Menasha lock (4)(18)(14). Electrodes that receive intermittent DC current will be imbedded in the walls and floor of the channel. A generator and battery backup system will exist to provide uninterrupted backup energy in case of a power outage.

The project will require soil grading and enlargement of impervious areas. This project may require below-grade piping, launch piers, and concrete stairs and walkways for access. Changes will need to be made in electric, gas, water and sewer utilities. (See attached Smith-Root proposal) (14, 1, 2, 4)

Electric Deterrent Technology

The electric fish barrier consists of intermittent DC generated electric current that passes between electrodes in the water to deter fish migration. (See Smith-Root proposal (17)).

Hydrologic Control - Water Velocity Barrier

The refereed scientific literature indicates that the movement of juvenile and adult round goby can be impacted by water velocity. (5) Juvenile round goby are subject to nocturnal diel vertical migrations. (5) Prior to any lockage, upstream water will be used to fill the lock; all six valves will be opened. In less than three minutes, 325,000 gallons of water will be rapidly discharged down the U-shaped channel. Newly hatched round goby fry can swim at roughly 4.4 cm/s (7). The existing hydrological structures (valves) in the lock doors provide an initial velocity of 14.3 fp/s that will control the upstream migration of both the fry and adult goby. (18)

Lock Operations

Smith-Root will develop a Standard Lock Operations Manual that will coordinate and define the use of the electronic/water velocity barrier. The manual will define the operational sequence that will ensure the proper water velocities are achieved to flush fish through the U-shaped channel. (See Smith-Root proposal) This combination of an electric deterrent barrier and hydrologic water velocity barrier will provide an acceptable solution that will prevent upstream migration of the round goby. The electric barrier will only be used during daylight lock operational hours from May to October.

Current & Future monitoring for AIS

AIS monitoring in the Fox River has been conducted by FRNSA since 2006 (21). Monitoring will continue and increase as needed. The objective is to identify and monitor any new AIS and, if necessary, modify the configuration and methodology used at the Menasha electric barrier to control the migration of AIS. (21)

Contingency Plan

There are two significant disadvantages in the development of a contingency plan. They are as follows:

1. It is assumed that any new AIS found upstream from the Menasha lock will have passed through the AIS barrier at Menasha lock. However, it has been demonstrated that AIS are present in pools upstream of the Rapide Croche invasive species barrier which has been in place since 1985. The presence of AIS upstream from the Rapide Croche barrier indicated that AIS did not spread through the lock system.

2. There are a limited number of response options for AIS control and eradication once AIS are present and established in new areas. For this reason, FRNSA will take a more proactive position in monitoring and preventing the upstream migration of AIS through the AIS barrier at the Menasha lock. (15)

Requested Action

FRNSA requests DNR approval for construction of an electric/water velocity AIS barrier immediately downstream of the Menasha lock to control round goby migration into the Lake Winnebago system and to allow the Menasha lock to be reopened.

SMITH-ROOT
Technology For Fisheries Conservation

Menasha Lock Fish Deterrent System
DRAFT Feasibility Study Report
Version 2

Prepared for Fox River Navigational System Authority

November 8, 2017

Document Control

DRAFT– August 21, 2017 Author – Jason Kent; Reviewer – Martin O'Farrell, Ph.D.

DRAFT VERSION 2 – November 8, 2017 Author – Jason Kent; Reviewer – Martin O'Farrell, Ph.D.

EXECUTIVE SUMMARY

Smith-Root performed a study of the feasibility of an electrical deterrent system with the purpose of preventing Round Goby (*Neogobius melanostomus*) and other invasive fish from migrating upstream into Menasha Lock on the Fox River and gaining access to Lake Winnebago. One location was identified between the lower lock gate and the excavated boat access channel downstream of the lock. Smith-Root evaluated three barrier configurations: one exclusive Round Goby barrier configuration that deters fish only along the floor of the barrier, and two configurations that produce a deterrent electrical field throughout the water column. All configurations include the construction of a concrete sill with vertical walls and steel bar electrodes on the floor of the sill; the full water column configurations require extension of the vertical walls and steel electrodes to the water surface.

Based on previous experience and research regarding electrical deterrence of Round Goby and other fishes, Smith-Root modeled the three configurations with selected deterrent voltage gradients and pulsed DC waveforms. The analysis of the modelling results assumed standard peak voltage output from Smith-Root BP-1.5 POW pulse generators.

Drawing upon Smith-Root's experience with similar facilities, and further confirmed by 3-dimensional electrical field modelling and analysis, Smith-Root believes a suitable system can be provided to deter Round Goby and other invasive species of fish in the Fox River from entering Menasha Lock. Two configurations are proposed: one configuration exclusively deters benthic species like Round Goby, and the second configuration deters passage of fish that utilize the entire water column. A hybrid approach is also feasible, in which the infrastructure for the full water column deterrent system is constructed but initially operated to exclusively deter Round Goby. In addition, the need for inducing water velocity through the barrier in order to minimize the immobilization/stunning of fish in the electric field should be assessed in more detail.

This report details the project scope, electrical field analysis, and deterrent system equipment recommendation. The report also includes a description of Smith-Root technology, safety, and examples of previous electrical barrier installations. A preliminary cost estimate of design, supply of Smith-Root equipment and monthly operational cost is provided, as well as costs for Smith-Root personnel to provide commissioning and training of staff. Cost to construct is not estimated in this report and an assessment of constructability is not provided.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AWG	American Wire Gauge
Cfs	Cubic feet per second
cm	Centimeter
DNR	Department of Natural Resources (Wisconsin)
FBTCS	Fish Barrier Telemetry and Control System
FRNSA	Fox River Navigational System Authority
ft	Feet
ft/sec	Feet per second
HADS	Hydrometeorological Automated Data System
Hz	Hertz
kcmil	Thousand circular mils. 1 kcmil = 0.5067 square millimeters
Km	Kilometer
M	Meter
ms	Millisecond
ft/sec	Feet per second
µS	MicroSiemens
OD	Outside Diameter
PFD	Personal Flotation Device
POW	Programmable Output Waveform
sec	Second
UPS	Uninterruptable Power Supply
USACE	United States Army Corps of Engineers
USD	United States Dollar
USGS	United States Geological Survey
V	Volts
kW	Kilowatts
kWh	Kilowatt Hours

BACKGROUND

Menasha Lock is situated on the outlet of Lake Winnebago in Menasha, Wisconsin, and is the upstream-most lock on the Fox River Navigational System. The first lock was built at the site in 1856. The current lock was constructed in 1970, and underwent repairs in 2014. The lock, constructed of concrete and steel and 144 feet long by 35 feet wide, has a total lift of 9.7 feet. The lock and most of the area surrounding the lock is owned by the Fox River Navigational System Authority (FRNSA); the dam on the southwest side of the lock is owned and operated by the U.S. Army Corps of Engineers (USACE). A small excavated boat access channel on river right (looking downstream) exists about 140 feet downstream of the lower lock gates; this basin is privately owned and is often used by personal watercraft owners to put in and take out their boats and for portage around the lock. Lake Winnebago is upstream of the lock, and downstream of the lock the reach of the Fox River is known as Little Lake Butte Des Morts.

In September 2015, FRNSA closed the lock to comply with the Wisconsin invasive species rule (Wisconsin Administrative Code chapter NR40). Among other things, the rule bans transport of invasive species in two categories: "prohibited" and "restricted." The lock remains closed as of this writing.

One invasive fish present in Little Lake Butte Des Morts that is in the "restricted" category is Round Goby (*Neogobius melanostomus*), a fish native to Europe and Asia that has expanded its range in the Great Lakes region of the United States and Canada since at least the early 1990s.

The purpose of the feasibility study is to evaluate the power demands for a set of alternative deterrence systems that can conceivably be constructed downstream of the Menasha Lock. The deterrence systems integrate Smith-Root electrical pulse generator units and different configurations of steel electrodes. Each alternative is evaluated for feasibility using a quantitative electrical field simulation and preliminary estimate of cost of equipment.

This feasibility study report includes the following components:

- Site description;
- Deterrent system description and key factors;
- Feasibility analysis;
- Recommendation, including equipment requirements and maintenance programs; and
- Estimated costs of deterrent system equipment.

The data used in this study report were provided by FRNSA, USACE, United States Geological Survey (USGS) and Wisconsin Department of Natural Resources (DNR). Smith-Root engineer Jason Kent visited Menasha Lock and other locks on the Fox River Navigational System on April 27, 2017, with Dr. S. Timothy Rose and Mr. Robert J. Stark of FRNSA.

Menasha Lock Physical and Hydrologic Characteristics

The Menasha Lock is built in an earth fill dam that separates the Menasha Channel of Lake Winnebago from Little Lake Butte Des Morts (Fox River). The lock and the land immediately surrounding it is owned by FRNSA, and the dam is operated by USACE. Immediately downstream of the lock, wingwalls connect the lock structure to the surrounding banks. An excavated boat access channel is in place about 110 feet downstream of the lock structure on river right; a small, vegetated peninsula separates the approach to the lock from the main Little Lake Butte Des Morts channel for 250-300 feet on river left. The lock and surrounding area is shown in Figure 1.

USACE provided a spreadsheet containing hourly water level data at a gauge station on the Fox River at Fritse Park in Menasha for the period 11 October 2011 through 30 June 2017. The gauge is a Hydrometeorological Automated Data System (HADS) station owned by the National Weather Service; this particular station is served by USACE. The station measures instantaneous gauge height readings that refer to the level of Little Lake Butte Des Morts in the IGLD 85 vertical datum. This station is very near Menasha Lock, being on the opposite bank of the river from the lock. Within the measured period, the lake varied in elevation by 4.09 feet. Assuming a conversion of -0.855 ft from IGLD 85 to IGLD 55[1], the highest measured elevation of Little Lake Butte Des Morts during the given period at this location was 739.145 feet. Comparing this elevation to the constructed lock floor elevation, the maximum depth during the given period was about 11.3 feet.

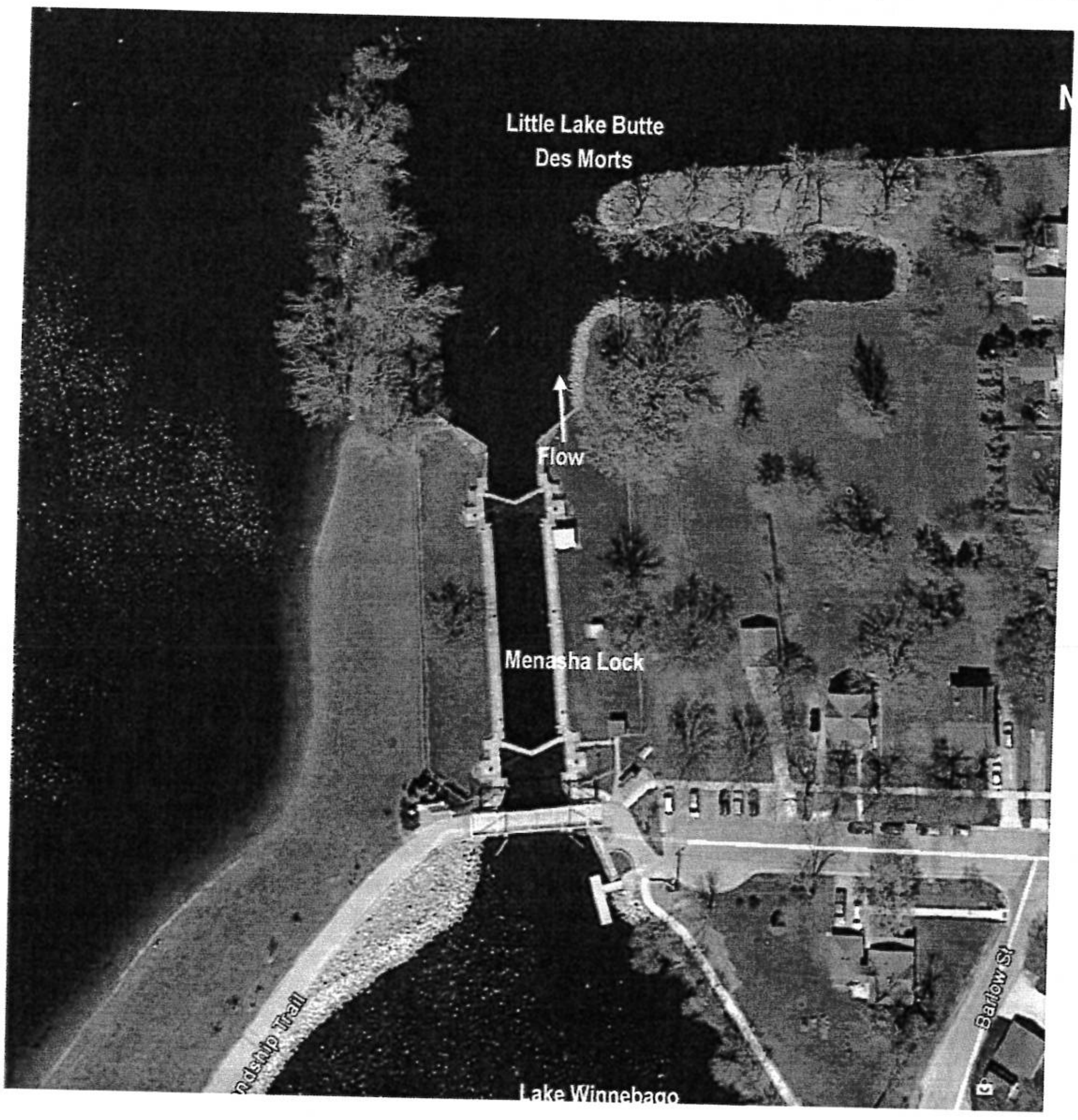


Figure 1. Aerial photograph of Menasha Lock (Photo credit: Google Earth)

[1]http://www.lre.usace.army.mil/Portals/69/docs/GreatLakesInfo/docs/IGLD/BrochureOnTheInternationalGreatLakesDatum1985.pdf, rough estimate to Lake Michigan benchmark

Invasive Aquatic Species of the Fox River

In an email dated 5 June 2017, Wisconsin DNR submitted a prioritized list of fish subject to NR40 for Smith-Root's consideration during the feasibility study (Table 1). With the exception of Round Goby, none of the fish in the list are currently found in the Fox River upstream of Rapid Croche Lock and Dam, and the relative likelihoods of these species being present in the river at some point in the future is unknown.

Table 1. Prioritized list of Aquatic Invasive Species (fish only) per Wisconsin DNR (5 June 2017)

Priority	Fish	NR40 Status
1	Round Goby	Restricted
2	Sea Lamprey	Restricted
3	White Perch	Restricted
4	Ruffe	Restricted
5	Grass Carp	Prohibited
6	Red Shiner	Prohibited
7	Rainbow Smelt	Restricted
8	Alewife	Restricted
9	Redear Sunfish	Restricted

All the fish in the list above have the ability to migrate upstream in multiple vertical positions of the water column with the exception of Round Goby. In addition, Sea Lamprey typically migrates along the substrate in locations with high velocity; this type of condition would not be typically found at the Menasha Lock fish deterrent system.

Smith-Root prepared this feasibility study with the approach of prohibiting upstream migration of adult lifestages of the fish in the list above. As will be addressed, there is one configuration that only addresses the benthic species Round Goby; this configuration can be combined with others to provide lower power deterrence for gobies only, if required.

Smith-Root Electric Deterrence Technology

Fish are sensitive to electrical currents because their muscles are controlled by electrical impulses via their nervous systems, and because they inhabit an electrically conductive environment. Electric barriers, deterrent systems and guidance structures make use of this sensitivity. Fish will encounter an electric field and experience strong discomfort (the voltage gradient is felt from head to tail) if they progress through the electrified zone. To reduce their discomfort, fish either turn around and exit the field or turn sideways to reduce the voltage gradient. Through many years of experience and research with electrofishing and barrier projects, Smith-Root has found configurations and settings that can produce the desired responses while minimizing injury or trauma to the target species.

Fish Deterrent System

Depending on the needs of the project, Smith-Root's technology can be designed as a barrier/deterrent system or as a guidance system. The electrical fish barrier is designed to be an impassable barricade, and the fish guidance system as a less intense repelling zone. Both use electrical current passing through water. The circuit is made up of two or more metal electrodes submerged in water with a voltage applied between them. Electric current passing between the electrodes, via the water medium, creates an electric field. When fish are within the field, they become part of the electrical circuit with some of the current flowing through their body. This can evoke reactions ranging from a slight twitch to full paralysis, depending on the current strength, pulse frequency and pulse duration they encounter.

Electricity Requirements

The pulsed DC deterrent system may be powered by AC from a locally accessible grid power source or a generator. A backup power supply, usually in the form of a generator, is recommended for critical applications, such as the blocking of an invasive species. The period between power shutdown and the start-up of the backup generator presents an unpowered gap in the power supply; an uninterruptable power supply (UPS) system is recommended in critical applications to address this gap. Smith-Root considers the inclusion of a generator and UPS system as optional and a policy decision to be made by the client.

Water Conductivity

Water conductivity is usually expressed as microSiemens per centimeter (µS/cm). The higher the water conductivity, the more freely electric current flows in water. Increased conductivity means more electric current is required to maintain an electric field through the water. Smith-Root designs solutions for water from very low conductivity (less than 20 µS/cm) up to about 5,000 µS/cm. The technology is suitable for applications ranging from pure freshwater to mildly saline estuarine sites.

Equipment and Monitoring

The barrier/deterrent system or guidance system is driven by electric power and complex electronic and communication components. Computer software controls the overall function, monitoring and telemetry system. The equipment components need to be placed in a location within an existing structure, a new building/enclosure or a trailer in order to protect the equipment from inclement weather and air temperature extremes that could cause damage. Ideally, the Smith-Root electronic equipment should be placed no farther than 100 feet from the electrodes to limit the voltage drop in the power delivery cables; however, provision can be made for longer distances by increasing the diameter of the cables. A more detailed breakdown of selected system components follows.

Electrical Pulse Generators:

Each Smith-Root Programmable Output Waveform (POW) pulse generator (also referred to as a pulser) generates output up to either 1.5 or 5.0 kilowatts (kW); several pulsers can be combined for one application. In addition, larger pulsers with higher power output may be built when demand warrants. Pulsed waveforms and frequencies can be programmed for optimum fish blocking or repelling. Pulse width is adjustable between 0.1 and 10.0 milliseconds. The repetition rate is adjustable between 0.5 to 100 hertz (Hz). The pulse generator produces a wide range of DC pulse outputs to give more stopping power with less stress to fish. Each of the POW pulsers, 11 of which are shown assembled for the Rygenefossen barrier in Norway in Figure 2, includes a microprocessor to control output pulse frequency and pulse width. A variety of waveforms can be generated: standard pulses, sweeping pulse widths, sweeping frequencies, and gated bursts. This allows generation of optimum waveforms that are effective for a wide range of species.

Fish Barrier Telemetry and Control System (FBTCS):

The Smith-Root Fish Barrier Telemetry and Control System (FBTCS) sets up, monitors, and controls the pulse generators via a fiber optic network. Figure 3 depicts a typical layout for the pulse generating system. Pulsers are connected through a communications and I/O controller hub between the monitoring computer and individual pulsers. The advantage of this arrangement is that, should any pulser in the system fail, the barrier will remain operational without disrupting communications with the remaining pulsers. A separate trigger loop keeps the pulser outputs synchronous as required by the system. The FBTCS also has connections to control external devices, such as flow meters, water quality meters, or depth sensors. The system can be expanded to monitor and/or control up to 256 devices by adding a custom interface board. The control system reports to remote monitoring locations via broadband or dial up modem or wireless connection.

The FBTCS can also receive remote commands to reconfigure the pulser outputs. When connected by modem to a computer, the FBTCS presents menus allowing remote control and monitoring. Passwords are used to prevent unauthorized access. The system software provides a status display, and a keystroke calls up the menus to give access to all functions. An event history is maintained to record error conditions.

Figure 2. Control room layout with Smith-Root pulse generators.

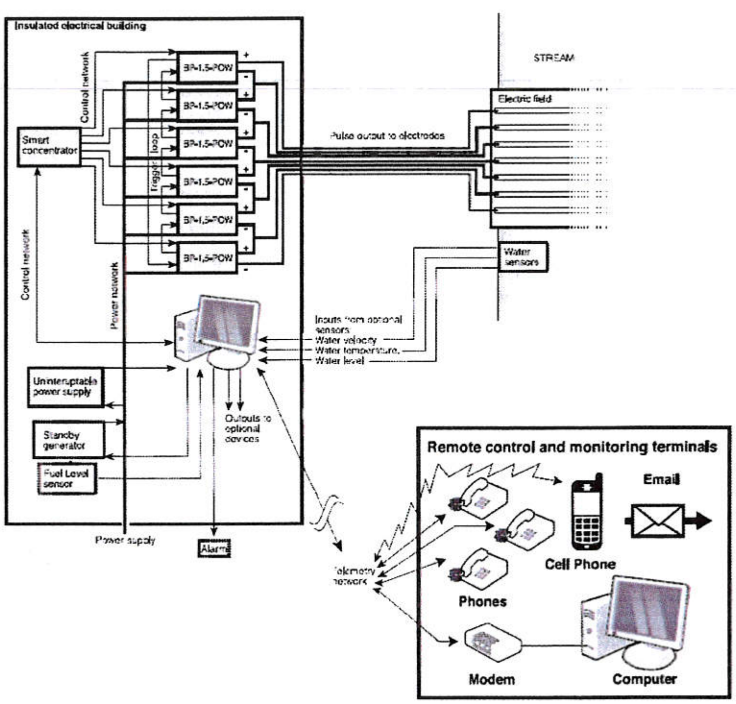


Figure 3. Typical system schematic.

Boat Movements in the Electric Deterrent System

Safe bidirectional movement of boats is the purpose of the operation of the Menasha Lock. Accordingly, Fox River Navigational System Authority seeks assurances that electrical fish deterrent technology safely allows boat traffic while also effectively blocking upstream fish migration.

Smith-Root electrical barriers are fully compatible with safe bidirectional boat passage of closed-hull boats. As is common sense for boat operators, Smith-Root recommends all boat passengers properly wear appropriate personal flotation devices (PFD) when crossing an active electrical barrier. FRNSA may consider requiring PFD use as policy for boats using the Menasha Lock.

However, Smith-Root recommends caution to users of small personal watercraft such as canoes, kayaks, stand up paddleboards, jet skis and wave runners in an active electrical barrier. Best practice can be to require these small craft to portage around the lock, or to utilize the lock only when the barrier is not functioning or in the case the deterrence field is limited to the bottom of the channel. The appropriate policy for these personal, open-hull watercraft should be developed concurrent with design of the electrical barrier.

Human safety is covered in more depth in the Recommendations section of this report.

FEASIBILITY STUDY

Potential deterrence systems at the selected location were modeled using COMSOL Multiphysics, a general purpose finite element analysis software, and analyzed for electrical field characteristics and power consumption. The results of the analysis are described in this section. The equipment needed to produce the electric field, along with price estimates for the equipment and predicted operating costs, are described in the Recommendations section.

Following the submittal of the initial draft report, FRNSA requested the evaluation be expanded to consider options inside the lock chamber. This version of the draft report includes detailed description of one such scenario throughout the report, and a general discussion of lock deterrence systems is included in the Discussion section.

Key Factors

Target Fish Species and Lifestage

Wisconsin DNR has identified several non-native species of fish currently present in Lake Michigan that are restricted by regulation from entering Lake Winnebago; these fish species are described in greater detail in the *Invasive Aquatic Species of the Fox River* section previously in this report (table 1, page 4). The objective of the barrier is to prevent the passage of non-native fish from the Fox River into Lake Winnebago. As of this writing, Round Goby is the only fish in Table 1 that has been detected in the Fox River upstream of the barrier at Rapide Croche Lock & Dam. All alternatives described and evaluated subsequently in this report are designed to prevent upstream migration of Round Goby at a minimum. One alternative presented later in this report is designed to exclusively deter Round Goby, as will be discussed.

While the barrier design and specifications will provide deterrence for Round Goby, FRNSA requested the development of alternatives that additionally deter upstream migration of fish on the Wisconsin DNR table that are not presently found in the Fox River above Rapide Croche. Because the swimming strategies of these fish differ so markedly from that of the benthic Round Goby, the layout of the electric barrier alternatives are much different in scale and cost than the "benthic fish only" alternative.

The target fish species and lifestages evaluated in this feasibility study report are summarized as:

1. Configuration 1 – Downstream of lower lock gate; deters benthic species only.
2. Configurations 2 & 3 – Downstream of lower lock gate; deterrence electric field administered to full water column (to level of Little Lake Butte Des Morts).
3. Configuration 4 – Upstream and downstream of lower lock gate; deterrence electric field administered to full water column (to level of Little Lake Butte Des Morts).

Round Goby have markedly different life histories than the other fish species indicated by Wisconsin DNR. They are benthic molluscivores, with adults almost exclusively preferring to remain on the substrate near their prey (Ghedotti et al. 1995, Savino and Kostich 2000, Kostel 2001, Hayden and Miner 2008). Adult gobies are not effective at feeding vertically in the water column (Ghedotti et al. 1995). One study conducted in the laboratory showed that prey on the aquarium wall only 20 cm above the substrate "appeared safe" from predation by gobies (Kostel 2001). However, juveniles have been known to rise in the water column at night to chase prey (Hayden and Miner 2008). Previous studies and experiments show that electrical barriers are effective in restricting volitional movements of adult Round Goby (Savino et al. 2001, McLaughlin and Phillips 2005). They have very fast burst speeds; in a slack water experiment speeds up to 1.6 meters per second were observed, although adults are capable of even faster burst speeds (Tierney et al. 2011). This means that a barrier should be designed with sufficient length and waveform to immobilize a Round Goby before its momentum can carry it through the barrier.

Barrier Location

During the Smith-Root site visit on April 27, 2017, discussions with FRNSA staff and board members and an employee of Wisconsin DNR led to decision to focus the location of the barrier on the approximately 100-foot zone downstream of the lower lock gate. Land on both sides of the lock confines the approach channel in this area, creating a convenient area for a barrier. Immediately downstream of the lower lock gate, the top of the lock walls are 749.30 feet IGLD 55[2] and lock floor elevation is 727.87 feet. Short, steel wingwalls expand the approach from 35 feet at the lock gate to about 95 feet within a 24 foot length downstream of the lock (0.8:1 expansion). Land on the banks, and presumably the bottom of the approach channel, are bare earth downstream of the ends of the wingwalls. A wide angle photograph of the proposed site is presented in Figure 4.

Figure 4. Photograph of proposed barrier location.

Locating the barrier inside the lock chamber has a different set of constraints, including the old concrete of the structure, the unknown (but likely shallow) depth of reinforcing steel, the need to overlay the lock chamber, the lower lock gates, and other metallic appurtenances with a dielectric coating or paneling, and the resulting narrowing of the lock chamber width after panel installation. One configuration that is partially located inside the lock chamber is described in this report.

In addition, an assumption was made that the small excavated boat access channel on river right downstream of the lock is to be avoided by any structures for fish deterrence.

Water Depth and Velocity

Depth of water in the proposed location of the barrier – immediately downstream of the lower lock gate – was discussed in the *Menasha Lock Physical and Hydrologic Characteristics* section previously in this report. In the period October 2011 to June 2017, the depth ranged approximately 7.2 to 11.3 feet.

[2] All given elevations in this report reference IGLD 55 vertical datum unless otherwise indicated.

Velocity data at the proposed barrier location has not been identified. The velocity at the proposed barrier location is likely zero, unless significant leakage is present through the lock gates, around or under the lock. No evidence exists that this is the case. During lock turn operations, the velocity in this area is temporarily high as the lock empties into Little Lake Butte Des Morts.

There are no current facilities for creating a steady flow through the proposed barrier location except by controlling a flow through the lock gates. If a steady discharge through the barrier is required for development of a barrier alternative, the hydraulic head difference and short distance between Lake Winnebago and the proposed barrier location can be leveraged by constructing a pipe or culvert with a shutoff valve adjacent to the lock.

Water Quality

Water conductivity, also referred to as specific conductance, is an important water quality parameter to consider in the design of an electrical deterrent system. Seven time series sets of water conductivity in the Fox River were obtained from USGS and Wisconsin DNR for analysis. A data set of 25 values collected by Wisconsin DNR near the Lake Winnebago outlet in Neenah, Wisconsin between 30 March 2015 and 28 March 2017 was selected because of its proximity, recentness, and relatively low standard deviation. The range of measured conductivity was 346 to 489 μS/cm, with a mean of 406 μS/cm.

Proposed Deterrent System Configuration

System Layout and Electrode Configurations

Smith-Root modeled four electrical deterrent system configurations at the proposed location. One configuration is designed to deter upstream migration of benthic fish only. The other configurations are designed to deter Round Goby and the other non-native fish species listed in Table 1. The first three configurations assumed an engineered channel immediately downstream of the lower lock gate at the same width as the lock (35 feet) that will contain all flows through the lock, and the electrical deterrent systems impart the deterrence field across the entire channel. The fourth configuration places the upstream end of the electrical deterrent system just upstream of the lower lock gate, and extends the system downstream to the end of (and slightly beyond) the existing wingwalls. All modeled configurations featured electrodes positioned perpendicular to flow. This arrangement also minimizes the system footprint and the water volume to energize.

Configuration 1: Exclusive Benthic Fish Barrier downstream of lower lock gate

The approach for an exclusive benthic fish barrier draws from research that Smith-Root performed in Michigan in 2015. The very strongly benthic locomotion pattern of the adult Round Goby means that it rarely rises more than a few centimeters above the channel bed, and the length of locomotion higher in the water column is very short (Kostel 2001). This allows an electric barrier to focus on the *channel bottom only* without the need for a deterrent voltage gradient above the bottom of the water column. The resulting barrier configuration can therefore have smaller electrodes spaced closer together along the channel bottom. The relatively long length of the barrier configuration is intended to deter Round Goby that may swim for a few feet higher in the water column on the downstream end.

Compared to other barrier configurations, this approach requires a lower capital cost to construct and requires less power to operate. The drawback is that the system is only effective at deterring truly benthic species – it will have little effect on fish that swim higher in the water column.

A schematic of Configuration 1 is presented in Figure 5. The deterrence system dimensions are as follows:

- Concrete sill dimensions: 35 feet wide by 37 feet long.
- Sill depth and wall dimensions: 8-12 inches deep slab, wall height 2 feet.

- Concrete sill and wall material: Electrically resistive concrete (Insulcrete™).
- Electrode dimensions: 2 inch x 1 inch bars, 35 feet long positioned perpendicular to flow.
- Electrode spacing: 2 feet on center.
- Number of electrodes: 17.

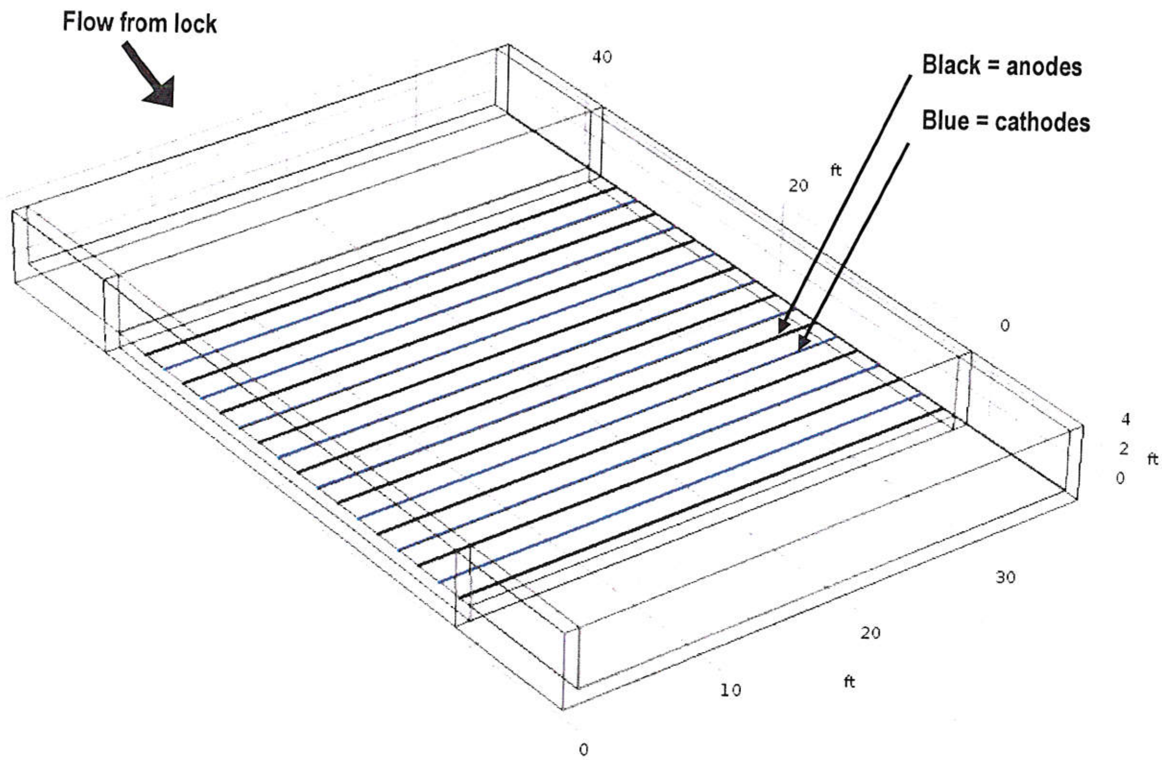


Figure 5. Schematic of Exclusive Benthic Fish Barrier

Configuration 2: Static Field Fish Barrier downstream of lower lock gate

Configuration 2 presents a deterrence electrical field to fish that utilize the entire water column for locomotion. A static field fish barrier incorporates a concrete sill that stretches across the approach channel with vertical walls that reach above the highest water surface with about 1 foot of freeboard. Seven U-shaped steel electrodes are affixed flush to the concrete sill and walls.

The electrodes present the electrical field within the barrier with deterrent voltage gradients up to the water surface. The deterrent voltage gradient is formed by increasing the voltage potentials at each electrode (in an upstream direction). The barrier pulse generator output will be set to provide 100 volts differential between each electrode in the barrier.

A schematic of Configuration 2 is presented in Figure 6. The deterrence system dimensions are as follows:

- Concrete sill dimensions: 35 feet wide by 37 feet long, 10-12 inches deep slab.
- Concrete wall dimensions: 12.3 feet tall by 37 feet long, 12 inches wide.
- Concrete sill and wall material: Electrically resistive concrete (Insulcrete™).
- Electrode number and dimensions: (7) 4 inch x 1 inch bars, positioned perpendicular to flow.
- Electrode spacing: 6 feet on center.

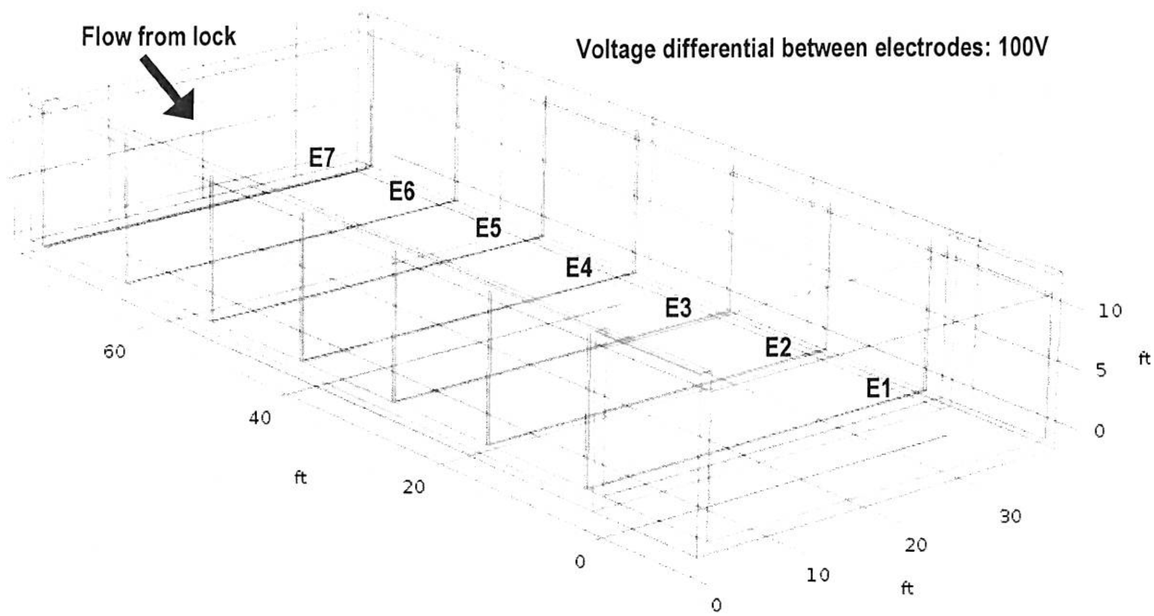


Figure 6. Schematic of Static Field Fish Barrier

Configuration 3: Graduated Field Fish Barrier downstream of lower lock gate

Configuration 3 is identical in structure to Configuration 2; the difference is in the voltage applied between electrodes. The same 100V differential is applied between each of the electrodes E1 and E4 – the downstream end of the barrier – and a higher voltage differential of 200V is applied between each of the electrodes E4 and E7. The result is a lower voltage deterrent field in the downstream half of the barrier that is intended to create a repulsion zone, and a higher voltage deterrent field in the upstream half of the barrier that can immobilize fish, barring their upstream movements.

A schematic of Configuration 3 is presented in Figure 7. The deterrence system dimensions are as follows:

- Concrete sill dimensions: 35 feet wide by 37 feet long, 10-12 inches deep slab.
- Concrete wall dimensions: 12.3 feet tall by 37 feet long, 12 inches wide.
- Concrete sill and wall material: Electrically resistive concrete (Insulcrete™).
- Electrode number and dimensions: (7) 4 inch x 1 inch bars, positioned perpendicular to flow.
- Electrode spacing: 6 feet on center.

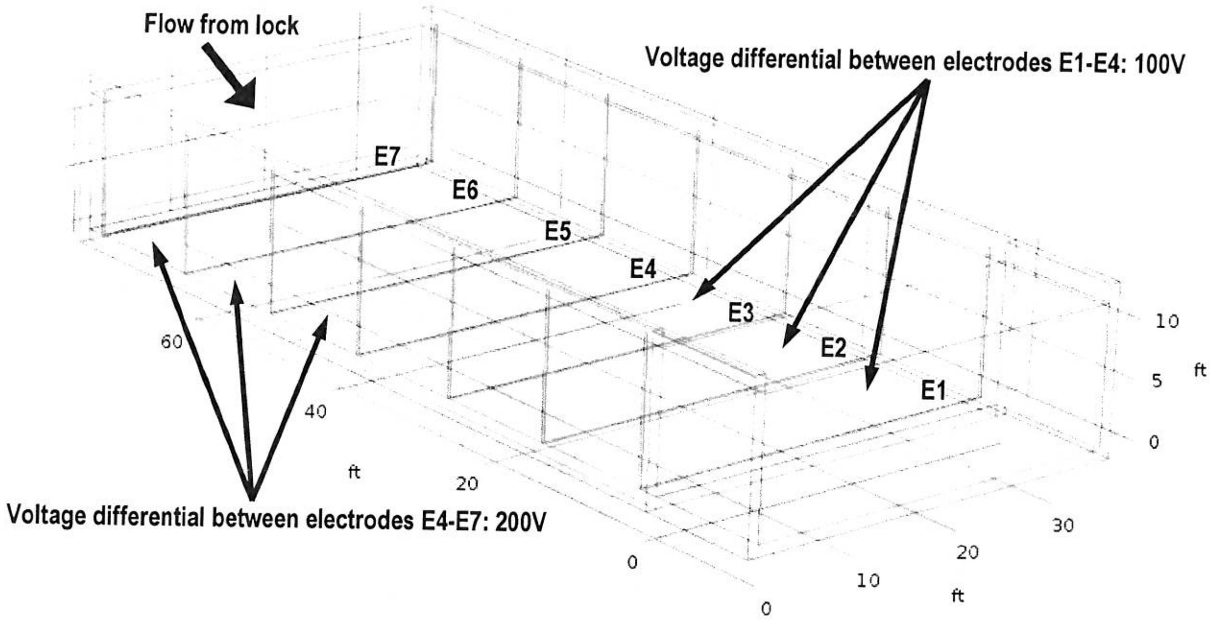


Figure 7. Schematic of Graduated Field Fish Barrier

Configuration 4: Graduated Field Fish Barrier that spans the lower lock gate

This configuration takes advantage of the lock gates as a physical barrier and integrates with the existing infrastructure. Electrodes are placed inside the lock that present a stronger electrical gradient that can immobilize fish, preventing their passage into the lock. This section of the barrier can be turned off when the lock gates are closed.

While this configuration is a GFFB, as is Configuration 3, there are major differences between the two:

- The barrier extends upstream into the lock, just south of the lower lock gate.
- The barrier expands with the wingwalls downstream to an 94-ft width at its end (no fill is needed).
- The ends of the wingwalls are extended downstream for 17.5 feet with a concrete sill.
- The upstream-most two electrodes, E6 and E7, are disconnected from the main system by a relay that turns the electric field off when not needed (i.e. when the lower lock gates are closed).
- The electrodes inside the lock only need to reach to the Little Lake Butte Des Morts water level – not to the top of the lock.

100V differential is applied between each of the electrodes E1 and E4, and 300V differential is applied between each of the electrodes E4 and E7. The result is a lower voltage deterrent field that creates a repulsion zone downstream of the lower lock gate, and a higher voltage gradient field near and around the lower lock gate.

A schematic of Configuration 4 is presented in Figure 8. The deterrence system dimensions are as follows:

- Barrier dimensions inside lock: 35 feet wide by 35.7 feet long, 12.3 feet tall (max. lake water level).
- Barrier wall material inside lock: 1.5" thick UHMW PE panels with embedded electrodes.
- Lower lock gate: Will need to be dielectrically coated to prevent electric current capture.
- Barrier dimensions downstream of lock: 35 feet wide expanding to 94 feet wide downstream, 40.3 feet long, 12.3 feet tall (max. lake water level).

- Barrier wall material downstream of lock: 1.5" thick UHMW PE panels with embedded electrodes on wingwalls, short Insulcrete™ (electrically resistive concrete) wall section 17.5 feet downstream of wingwalls.
- Barrier floor material downstream of lock: Insulcrete™ (electrically resistive concrete)..
- Electrode number and dimensions: (7) 4 inch x 1 inch bars, positioned perpendicular to flow.
- Electrode spacing: approximately 11.5 feet on center.

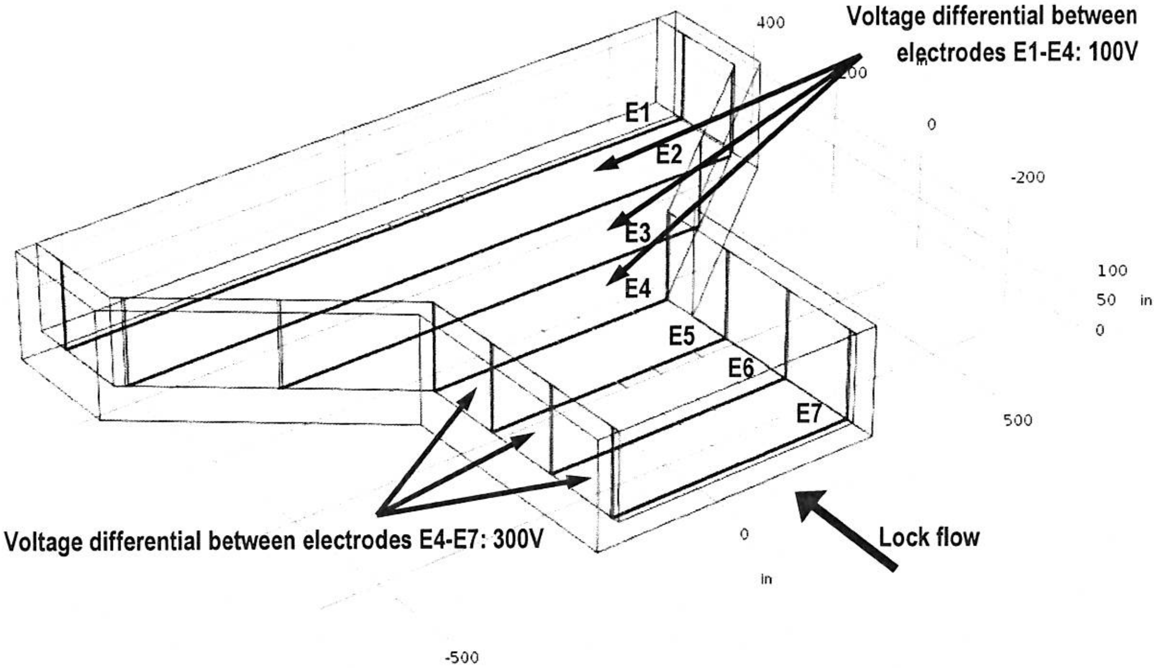


Figure 8. Schematic of Configuration 4. Note different perspective (flow to the upper left).

Electric Field Analysis

Preliminary electric field simulations have been conducted for the four electric barrier configurations at Menasha Lock. Smith-Root utilized a finite element analysis program, COMSOL Multiphysics, to apply the physics of electrostatics to conductive materials, thereby simulating electric field models in three dimensions.

Assumptions

- Water Conductivity – 509 µS/cm. As reported in the *Water Quality* section of this report, the measured range of specific conductance was 346 to 489 µS/cm, with a mean of 406 µS/cm. The data set included 25 values collected between March 2015 and March 2017. Because of the relatively low number of samples in the selected data set, Smith-Root added to the highest measured conductivity in the electrical simulation, introducing some conservatism to the analysis. When the Little Lake Butte Des Morts water conductivity exceeds 509 µS/cm, the power draw to the electrical pulse generating equipment will be higher. Conversely, the power draw is reduced when water conductivity is lower. It is recommended that specific conductance is routinely monitored and deviations from the assumed range of values are reported to Smith-Root.
- Electrically resistive concrete (Insulcrete™) conductivity – 20 µS/cm (assumed value).
- Water depth – maximum depth of 12 feet.

Target Deterrence Voltage Gradient

Based on past experience and recent research conducted in cooperation with the USGS Great Lakes Science Center, Smith-Root set the target voltage gradient for effective upstream deterrence of Round Goby at **2.54 V/in or greater.** Higher pulse rates are also indicated for Round Goby, up to 20 Hz, to effectively deter migration. Higher voltage gradients are also effective but consume more power.

Lower voltage gradients and frequency are preferred in slack water environments to prevent tetany and immobilization of fish. During periods of zero or very low flow in the barrier, no downstream current exists to "flush" an immobilized fish away from the electric field; the fish can be injured, killed, or drift through the field on its own momentum and recover on the upstream side of the deterrence field. Barrier design, particularly length of the deterrence field, considers the momentum issue and is designed to prevent immobilized fish from floating through the barrier.

However, it should be expected that fish that are immobilized in a slack water zone will not have the ability to leave the electric field volitionally. These fish may not survive. Round Goby individuals are negatively buoyant and will not float to the surface when immobilized, but other fish will rise to the surface. The only way to move immobilized fish away from the slack water zone is to induce a flow through the barrier. This point will be explored in further detail in the Discussion section.

Results

Configuration 1: Exclusive Benthic Fish Barrier

Results of the simulation that produced a minimum voltage gradient of 1.0 V/cm are given in Figures 9 through 11. Considering the 2-inch width of each electrode, the gap between electrodes is about 22 inches, and the Smith-Root BP-1.5 POW pulse generator is capable of voltage output of 56 V, 112 V and above. Thus the minimum voltage gradient of 2.54 V/in can be achieved with the lower voltage output setting. Figures 9 and 10 show a 2-dimensional field of voltage gradient coded by color, 6 inches off the bottom in Figure 8 and 4 feet off the bottom in Figure 10. The difference in the figures demonstrates the "decay" in electric field voltage gradient higher in the water column. Figure 11 further demonstrates this with voltage gradient along four paths through the barrier downstream to upstream. The voltage gradient is highest at the bottom, slightly more than 1.27 V/in) about 1 foot above the bottom, and close to zero at points 2 and 3 feet above the bottom (also at 4 feet above the bottom as shown in Figure 10). The figure also shows the "decay" higher in the water column; voltage gradient is very near zero at the water surface in this scenario.

Power output for this simulation is based on a duty cycle of 4% and a target voltage gradient of 2.54 V/in. A 4% duty cycle means that power is being delivered to the barrier 4% of the time, or 40 ms per second. For this configuration at 4% duty cycle, 840 W of output power would be needed.

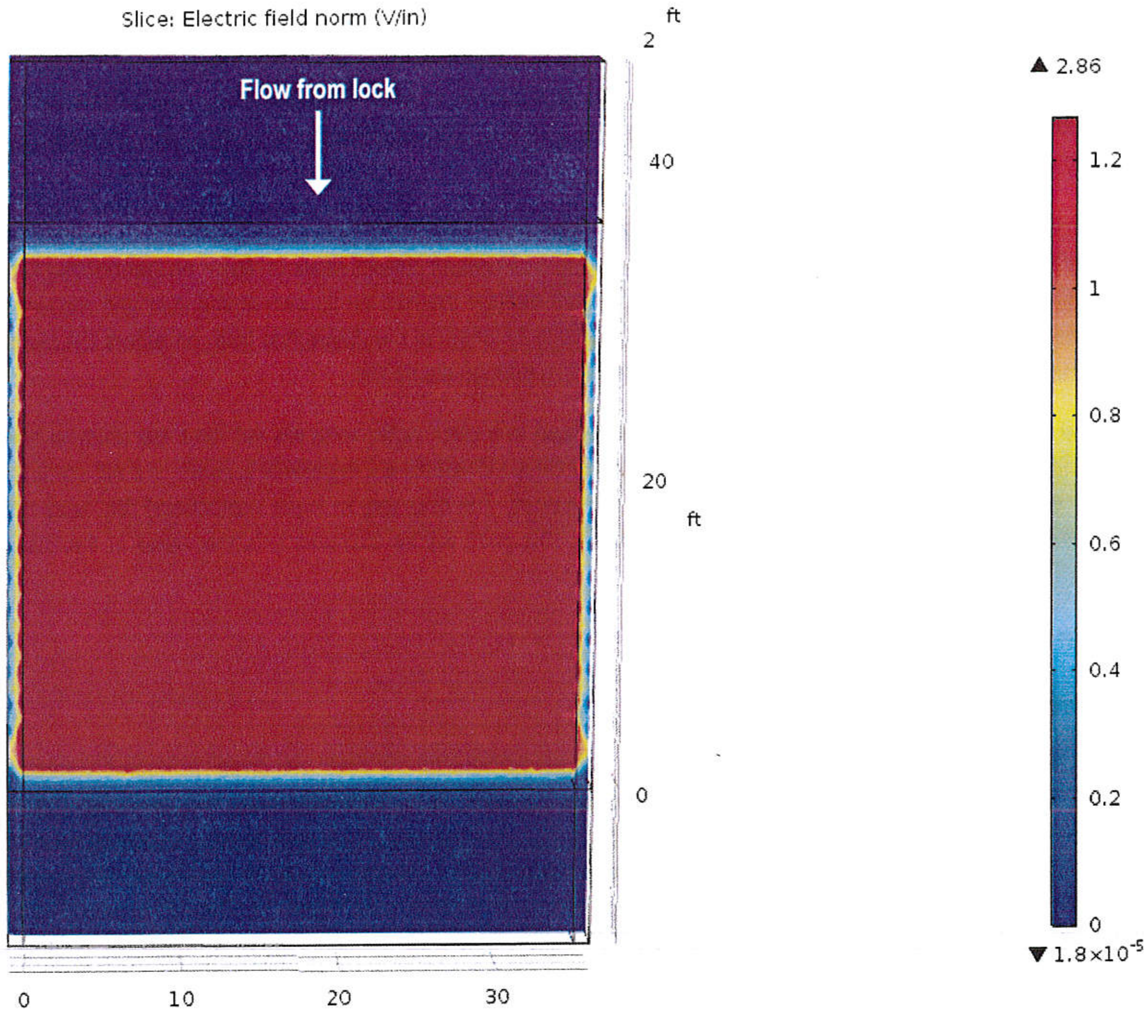


Figure 9. Plan view of Configuration 1 voltage gradient at 0.5 foot above the floor

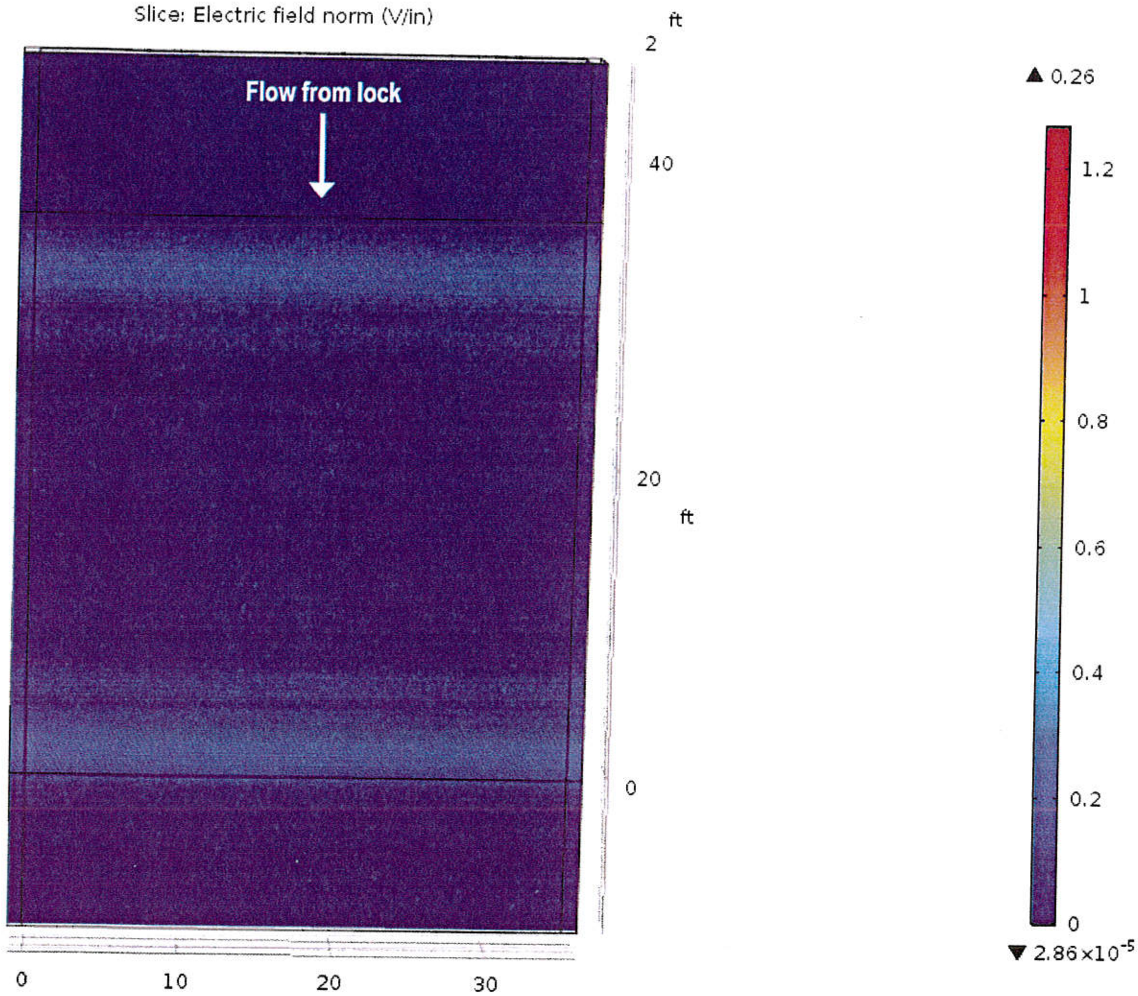


Figure 10. Plan view of Configuration 1 electrical gradient at 4 feet above the floor

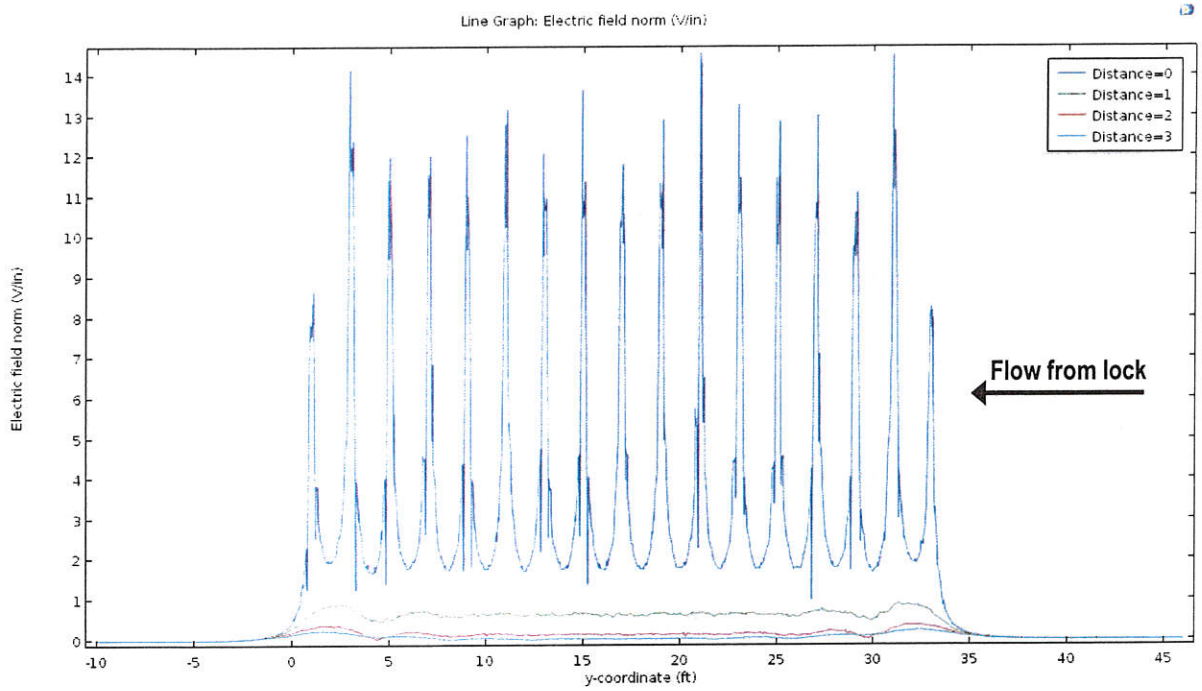


Figure 11. Cross section of Configuration 1 voltage gradient at multiple depths (in feet above floor)

Configuration 2: Static Field Fish Barrier

The Static Field Fish Barrier is a much different configuration than the exclusive goby barrier; seven electrodes convey the electrical field to the water surface with a higher power output. Figure 12 shows a plan view of the voltage gradient for a "slice" of the water column in the barrier at a plane 1 foot above the barrier floor. Figure 13 shows the same output at the water surface when depth in the barrier is 10 feet, and Figure 14 shows output along a vertical plane in the center of the barrier at 12 feet of depth. Figure 15 shows the voltage gradient along four paths through the barrier downstream to upstream. A voltage gradient above 2.54 V/in is present at two locations in the barrier, and a minimum 1.78 V/in gradient is present throughout the length of the 35-foot barrier.

Power output for this simulation is based on a duty cycle of 5% and target voltage gradient of 2.54 V/in. A 5% duty cycle means that power is being delivered to the barrier 5% of the time, or 50 ms per second. For this configuration at 5% duty cycle and adjusting output to achieve 2.54 V/in voltage gradient in the barrier, 5.3 kW of output power would be needed.

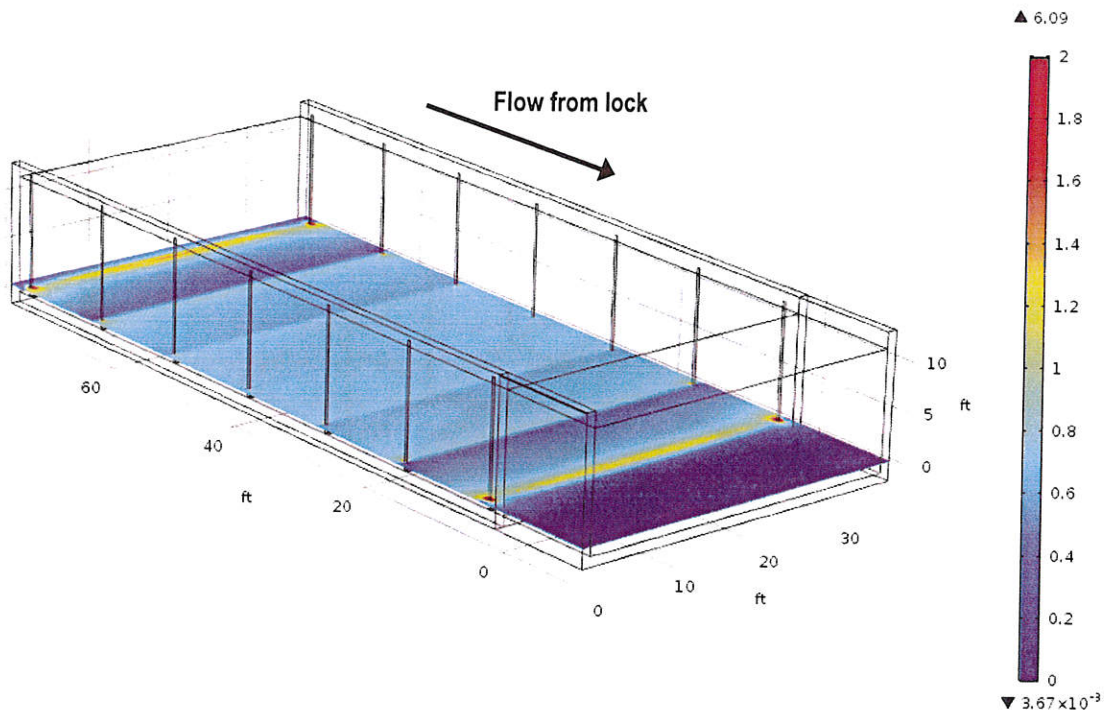


Figure 12. Plan view of Configuration 2 voltage gradient 1 foot above the floor

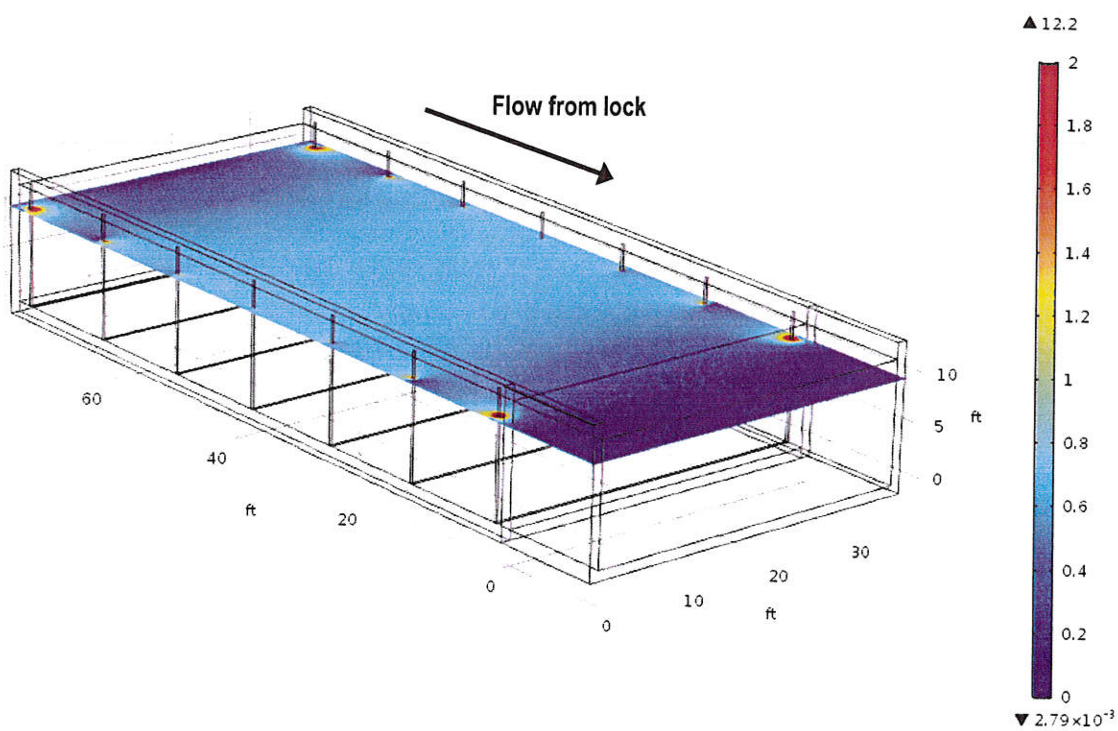


Figure 13. Plan view of Configuration 2 voltage gradient 10 feet above the floor

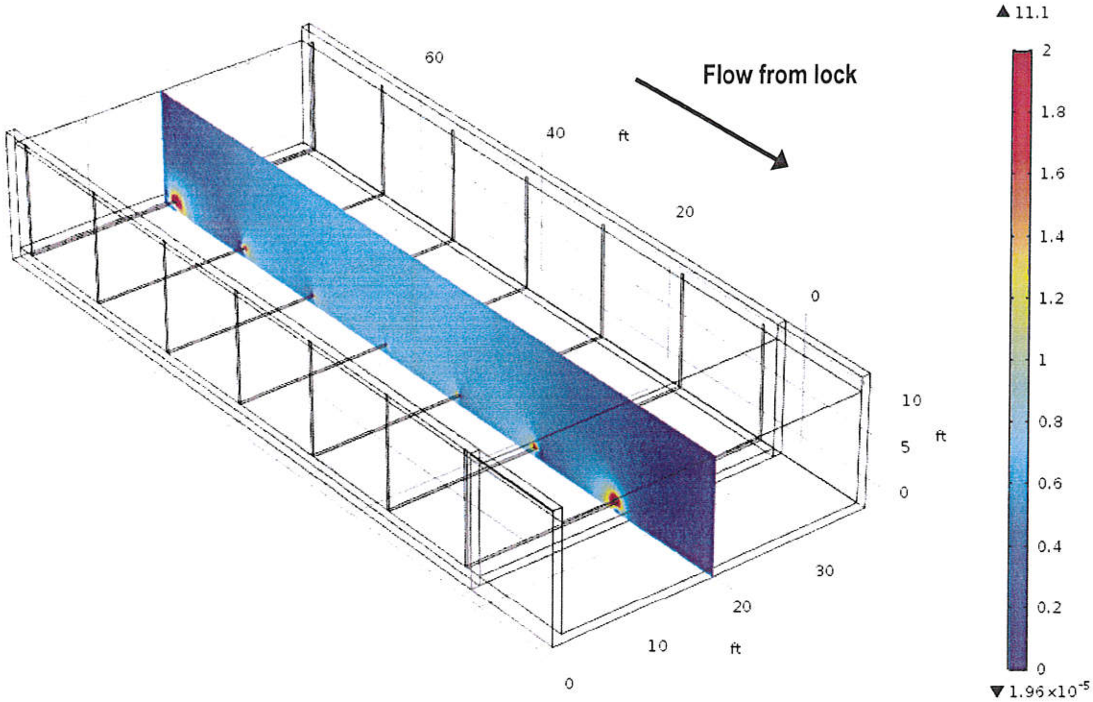


Figure 14. Cross section slice of Configuration 2 voltage gradient in center of barrier at 12 feet of depth

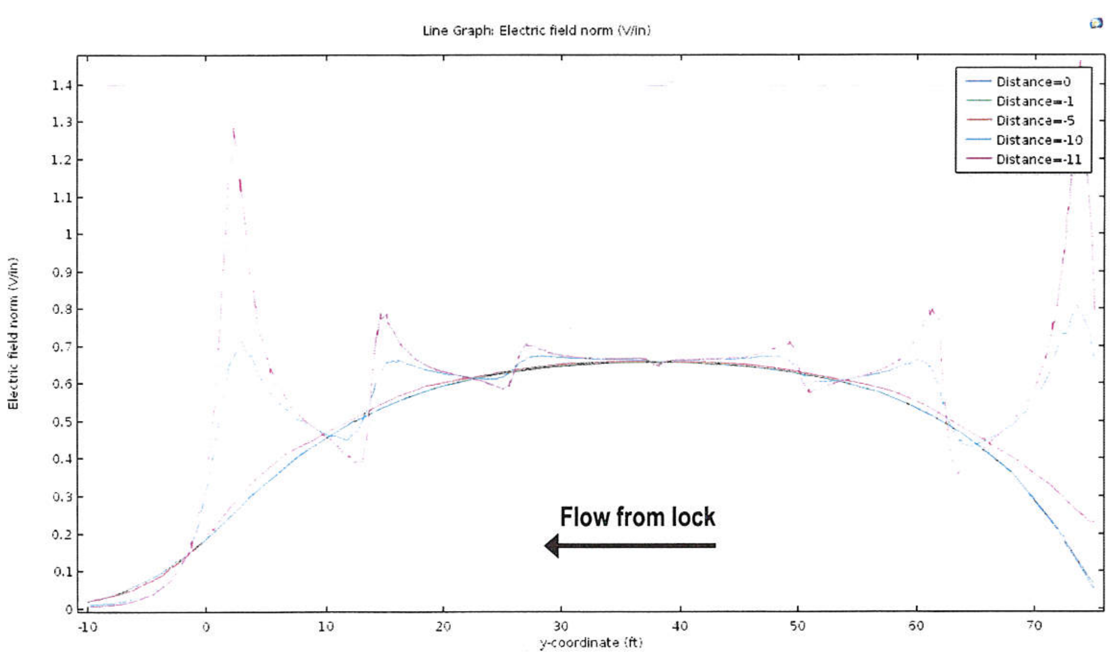


Figure 15. Cross section of Configuration 2 voltage gradient at multiple depths (in feet below water surface, depth = 12 feet)

Configuration 3: Graduated Field Fish Barrier

As previously discussed, the barrier layout in Configuration 3 is identical to Configuration 2; the difference is simply in the voltage applied between electrodes 4-7. The output at a horizontal slice of the water column at 1 foot above the floor and at the water surface (at 12 feet of depth) is shown in Figures 16 and 17. Figure 18 shows a vertical slice of output along the center line of the barrier with 12 feet of depth. The resulting voltage gradients along the center line of the barrier are shown at five distances below the water surface in Figure 19. The line graph clearly shows the "graduated" character of this configuration; maximum voltage gradient increases at all depths as a fish moves upstream in the barrier. This allows a fish in the water column to make a volitional decision about continuing upstream migration as the voltage gradient increases. Near the upstream end of the barrier, voltage gradients exceed 2.54 V/in and immobilization would be achieved.

Power output for this simulation is based on a duty cycle of 5% and a target voltage gradient of 2.54 V/in. A 5% duty cycle means that power is being delivered to the barrier 5% of the time, or 50 ms per second. For this configuration at 5% duty cycle and adjusting output to achieve 2.54 V/in voltage gradient in the barrier, 14.0 kW of output power would be needed.

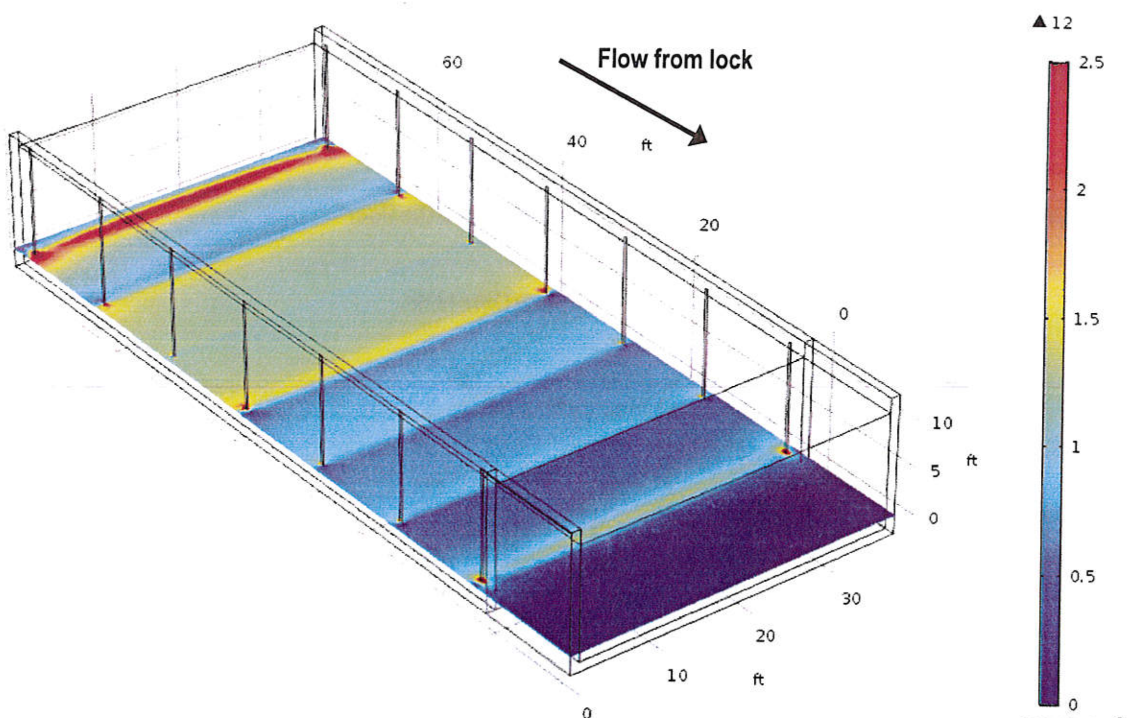


Figure 16. Plan view of Configuration 3 voltage gradient 1 foot above the floor

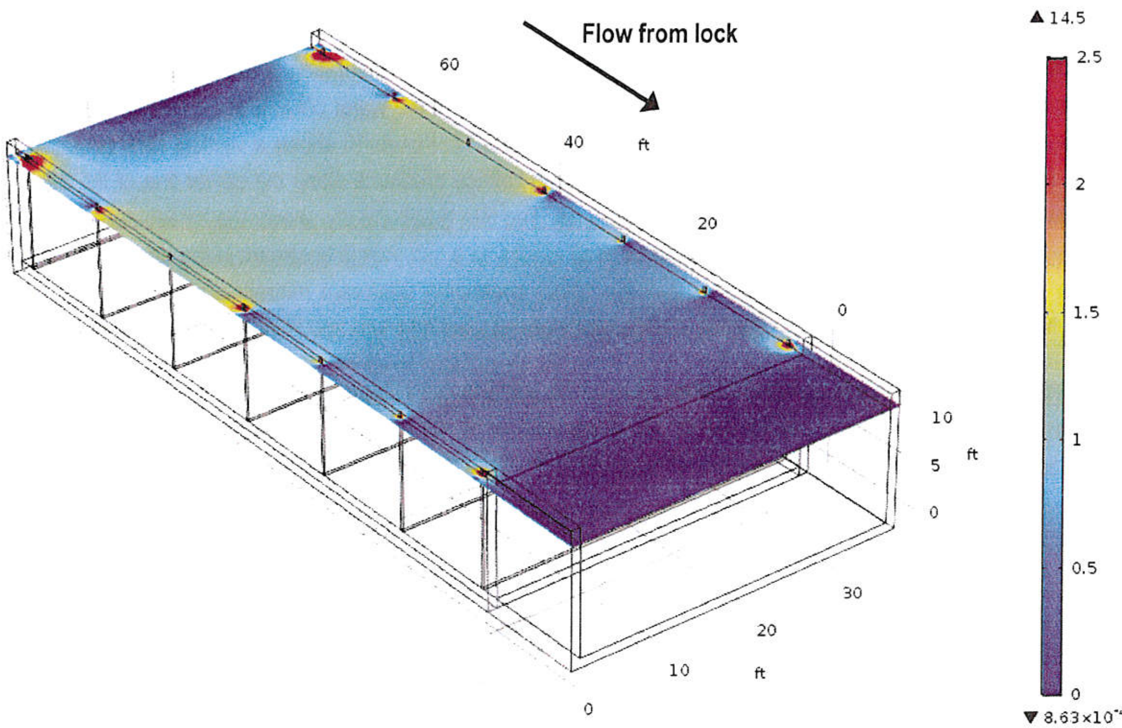


Figure 17. Plan view of Configuration 3 voltage gradient 12 feet above the floor

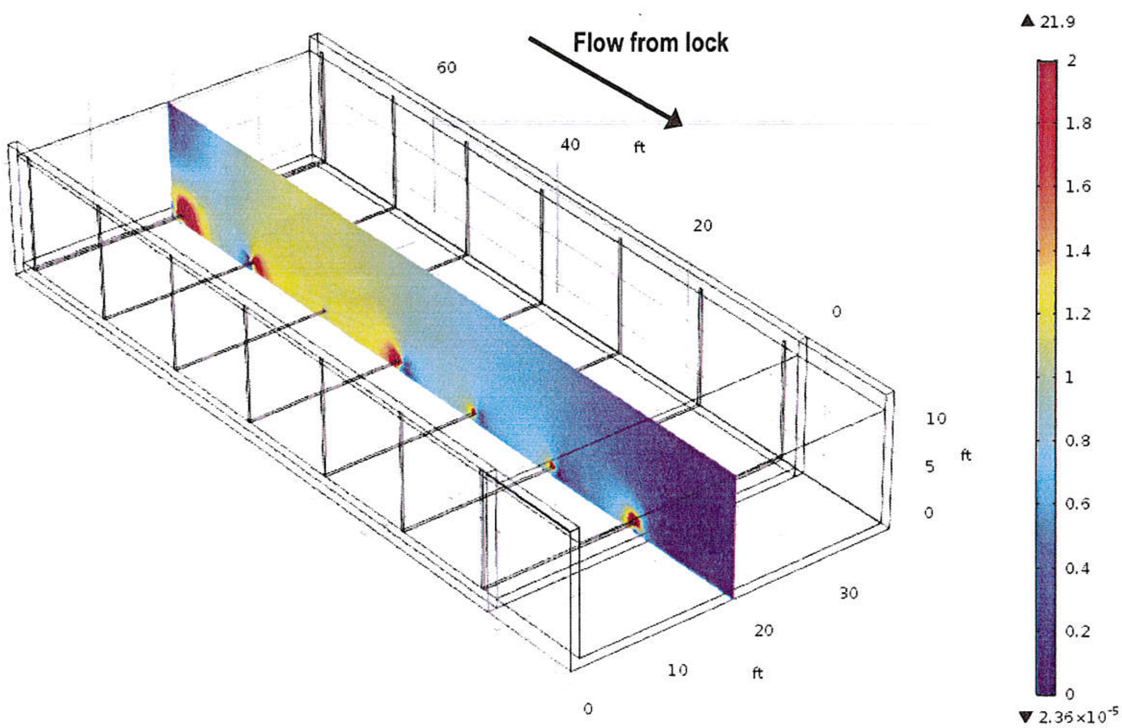


Figure 18. Cross section slice of Configuration 3 voltage gradient in center of barrier at 12 feet of depth

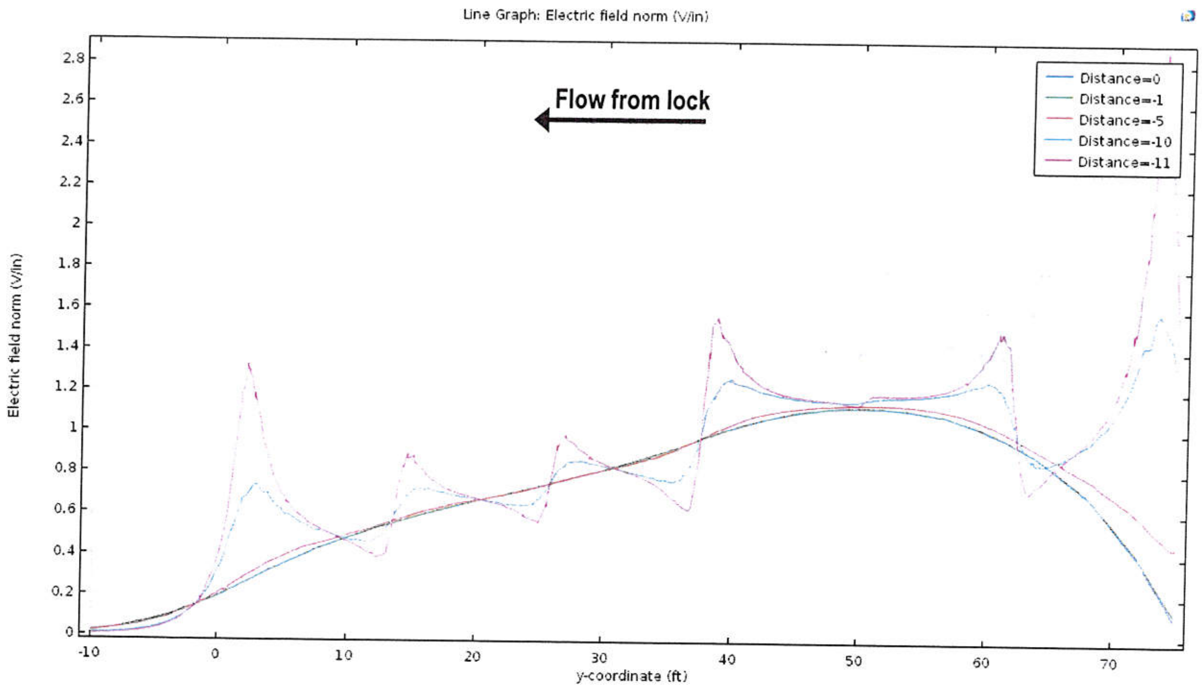


Figure 19. Cross section of Configuration 3 voltage gradient at multiple depths (in feet below water surface, depth = 12 feet)

Configuration 4: Graduated Field Fish Barrier that spans the lower lock gate

While Configuration 4 is a GFFB as is Configuration 3, this one is much different as it is much wider at the downstream end – necessitating more power to present an electric deterrence field to a larger volume of water – and it features essentially a two-stage system in which the upstream section can be turned off when the lower lock gate is closed. The output at a horizontal slice of the water column at 1 foot above the floor (with the Little Lake Butte Des Morts and Menasha Lock water level at 12 feet of depth) is shown in Figure 20, and Figure 21 shows the same results when the upper stage inside the lock is turned off and the lock gate is closed. The line graphs in Figures 22 and 23 show the graduated voltage gradient through the barrier profile for a fish swimming at three depths. This configuration shows the lower voltage gradient and the shorter length when only the downstream stage is on (Figure 23) compared to when both stages are operating (Figure 22). The line graph clearly shows the "graduated" character of this configuration; maximum voltage gradient increases at all depths as a fish moves upstream in the barrier. This allows a fish in the water column to make a volitional decision about continuing upstream migration as the voltage gradient increases.

Power output for this simulation is based on a duty cycle of 5% and a target voltage gradient at the upstream end (inside the lock only) of 2.54 V/in. A 5% duty cycle means that power is being delivered to the barrier 5% of the time, or 50 ms per second.

- When the lower lock gate is closed and only the downstream stage is operating – which would be a vast majority of the time – at 5% duty cycle the output power would be 1.4 kW.
- When the lower lock gate is open and both stages are operating at 5% duty cycle, and adjusting output to achieve 2.54 V/in voltage gradient in the barrier, the output power would be 11.3 kW.

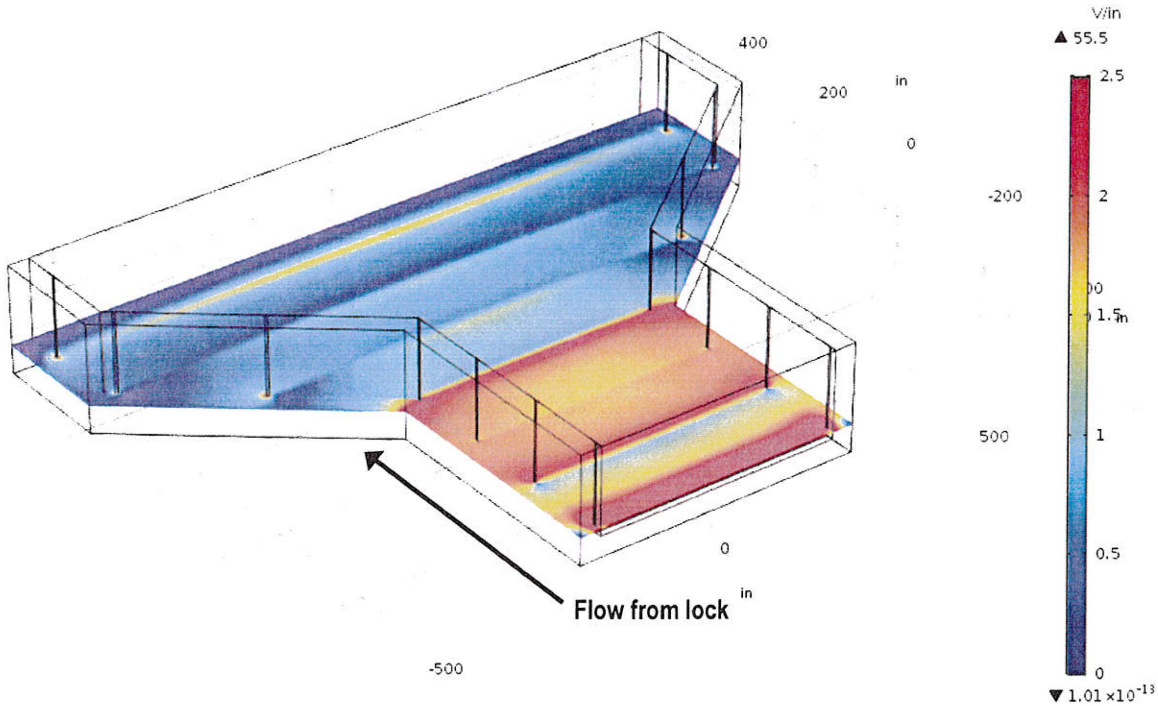


Figure 20. Plan view of Configuration 4 voltage gradient 1 foot above the floor

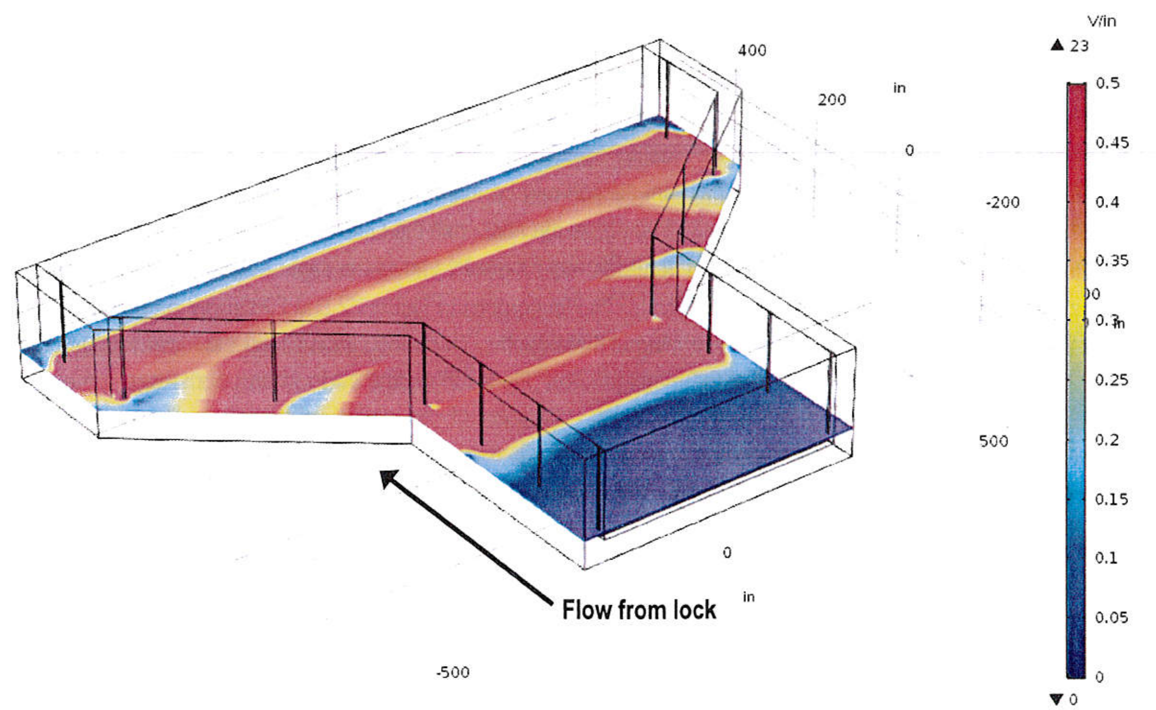


Figure 21. Plan view of Configuration 4 voltage gradient 1 foot above the floor with lower lock gate closed. Note: color scale is changed to highlight contrast in barrier sections.

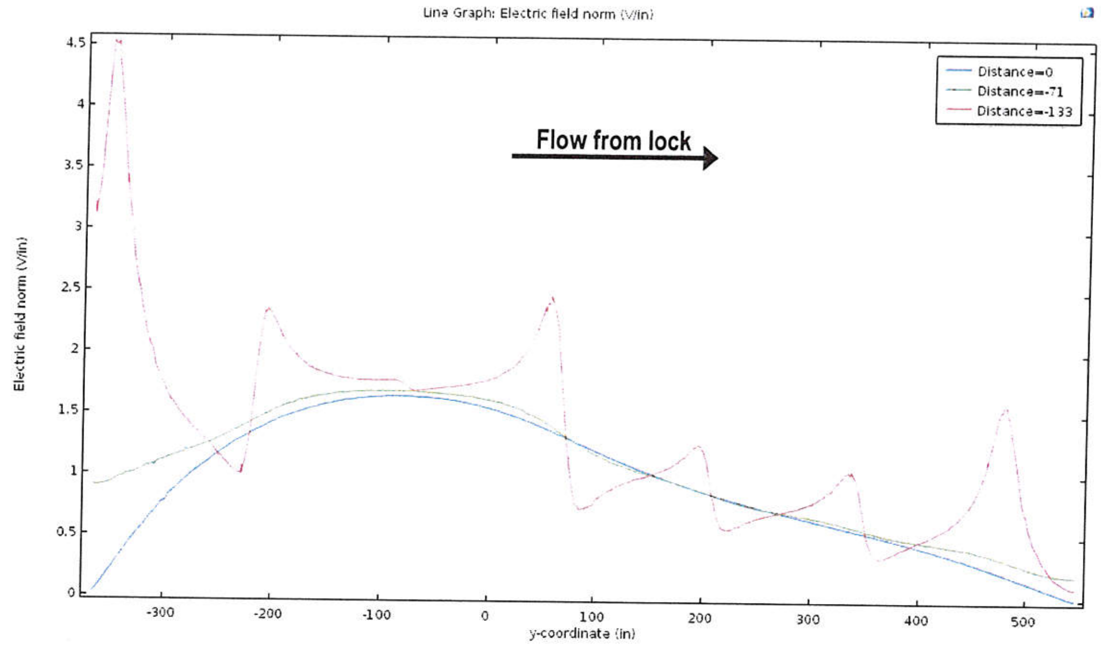


Figure 22. Cross section of Configuration 4 voltage gradient at multiple depths (in feet below water surface, depth = 12 feet)

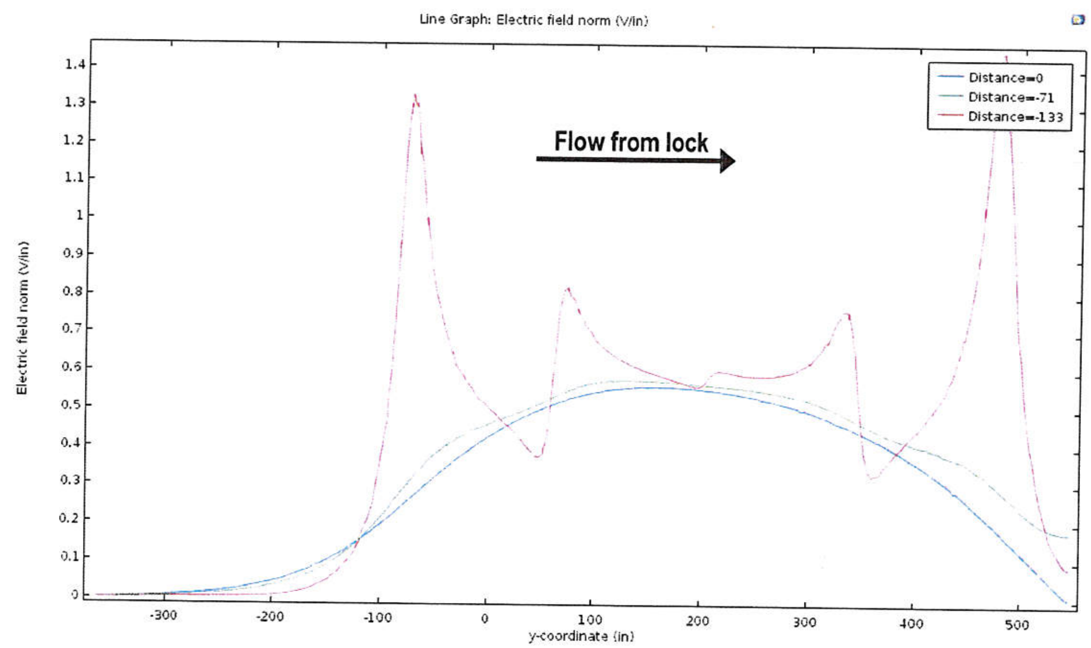


Figure 23. Cross section of Configuration 4 voltage gradient at multiple depths with lower lock gate closed (in feet below water surface, depth = 12 feet)

Discussion

The simulations show that the generation of a pulsed DC electrical field that can deter passage of Round Goby and other fish species identified by Wisconsin DNR into Menasha Lock is physically attainable. The capital and operating costs of the configurations considered in this report are discussed in the next section. The physical limitations of these barriers are discussed below.

Round Goby is a benthic-oriented fish, and can reasonably be expected to swim near the bottom of a channel at nearly all times (only the youngest fish tend to reach the water surface [Hayden and Miner 2008]). They have very fast burst speeds (Tierney et al. 2011), requiring a longer electric barrier to attain true deterrence. Configuration 1 is expected to be effective in deterring upstream migration of adult Round Goby, but because the deterrence voltage gradient does not extend very far above the bottom of the channel, this barrier will most likely not provide deterrence to other, pelagic species of fish.

In Configurations 2, 3, and 4, electrodes span the channel and the vertical walls of the barrier, producing an electrical field in the entire water column. The examples given for these configurations show stronger voltage gradients closer to the electrodes, particularly the electrodes that are most upstream in the barrier. Fish in close proximity to these higher voltage gradients may be immobilized. A key factor to the higher voltage gradient expected very near the electrode is the body length of a fish. Fish with longer body lengths "sense" a given voltage gradient at greater distances than smaller fish. This gives the fish an opportunity to avoid the system before tetany is induced – the result is a successful deterrence. A further mitigating factor is slower movement. In a slack water environment, fish moving at slower speeds sense an electrical field with enough time to change trajectory, resulting in deterrence.

Barrier operational strategy is a subject that is not fully discussed in this study. Depending on the operation of the lock, the barrier may not need to be "on" at all times. If the barrier is turned off for significant periods, a "soft-start" waveform may be applicable that incorporates rates of lower pulse frequency and lower voltage gradients to allow fish to turn around and escape the barrier area. The upstream end of the barrier could retain the deterrence electric field characteristics to prevent upstream passage. An extra set(s) of electrodes may be needed to provide this extra benefit, and can be further investigated during barrier design.

The electrical field in Configuration 1 will be limited to the bottom of the water column. A very weak voltage gradient, if any gradient at all, would be detectable at the water surface. This condition may allow a policy decision for personal watercraft boats such as kayaks, canoes, wave runners, jet skis, and stand up paddleboards to utilize the lock while the barrier is operating. However, in these cases PFDs should be mandatory and lockages of these types of boaters should be monitored.

An issue that should be considered during planning of an electric barrier at Menasha Lock is the lack of a flow in the barrier vicinity. An electric barrier in slack water can lead to fish kills when fish are immobilized and are not "flushed" out of the barrier area by water flow to recover downstream. The public location of the lock and its draw as a tourist attraction may make fish kills an undesirable side effect of the barrier operation.

A solution to reduce the magnitude of fish kills in the barrier is to induce a flushing velocity – the exact minimum velocity is to be defined but can be considered around 0.5 ft/sec – through the barrier location. Smith-Root has identified three potential sources of water velocity through the barrier:

1. **Flow through the lock gates.** From an infrastructure standpoint, this is the simplest approach as it entails slightly opening the upper and lower lock gates to take advantage of the head difference across the lock. It is

unknown if the gates can operate in this way. This alternative would require significant coordination with USACE as it would shift the location of a portion of Lake Winnebago's outflow to the Fox River.

2. **Valve/pipe system adjacent to the lock.** This alternative also takes advantage of the head difference across the lock to pass water when needed. The system could be constructed adjacent to the lock to minimize system length as shown in Figure 24. Like the first alternative, operation of this system would require significant coordination with USACE as it would shift the location of a portion of Lake Winnebago's outflow to the Fox River.
3. **Pump-induced flow on downstream side of lock.** This alternative would be entirely located on the downstream side of the lock, reducing the level of coordination needed with USACE as Lake Winnebago outflows would not be altered. The alternative takes advantage of the existing layout downstream of the lock to pump water into the upstream end of the barrier. While recirculation is expected because there is no head differential across the pump, the current would circulate around to the opposite side of the vegetated island on the left side of the lock, keeping fish and debris away from the barrier. The pump outlet would be constructed across the island and into the barrier structure as shown in Figure 24. A float-mounted Venturi-style pump is a potential option; an example is the Flow Velocity Enhancement System by Natural Solutions, LLC (http://www.fishpassage.com/services.html).

This feasibility study does not further consider flows through the barrier, and cost to construct is not included in the report. However, Smith-Root recommends the evaluation of velocity inducement systems as the planning and design of an electrical barrier progresses.

Hayden and Miner (2008) studied vertical migration of Round Goby. The research indicates that while adult Round Goby are entirely benthic, juvenile gobies (under 10 mm total length) tended to migrate vertically in the water column at night, possibly following planktonic prey that also migrate vertically at night. The study did not indicate whether these juvenile fish migrated horizontally *after* their vertical migration, which would have obvious implications on the efficacy of a bottom-only electric barrier. The study did suggest, however, that the juvenile gobies migration pattern when they were higher in the water column were transported by water current; that is, they drifted with the current. Thus, inducing velocity in the barrier could provide mitigation for the juvenile Round Goby individuals that migrate vertically above the exclusive Round Goby barrier at night. More study into juvenile Round Goby migration would be required if the bottom-only barrier is selected for further analysis and design.

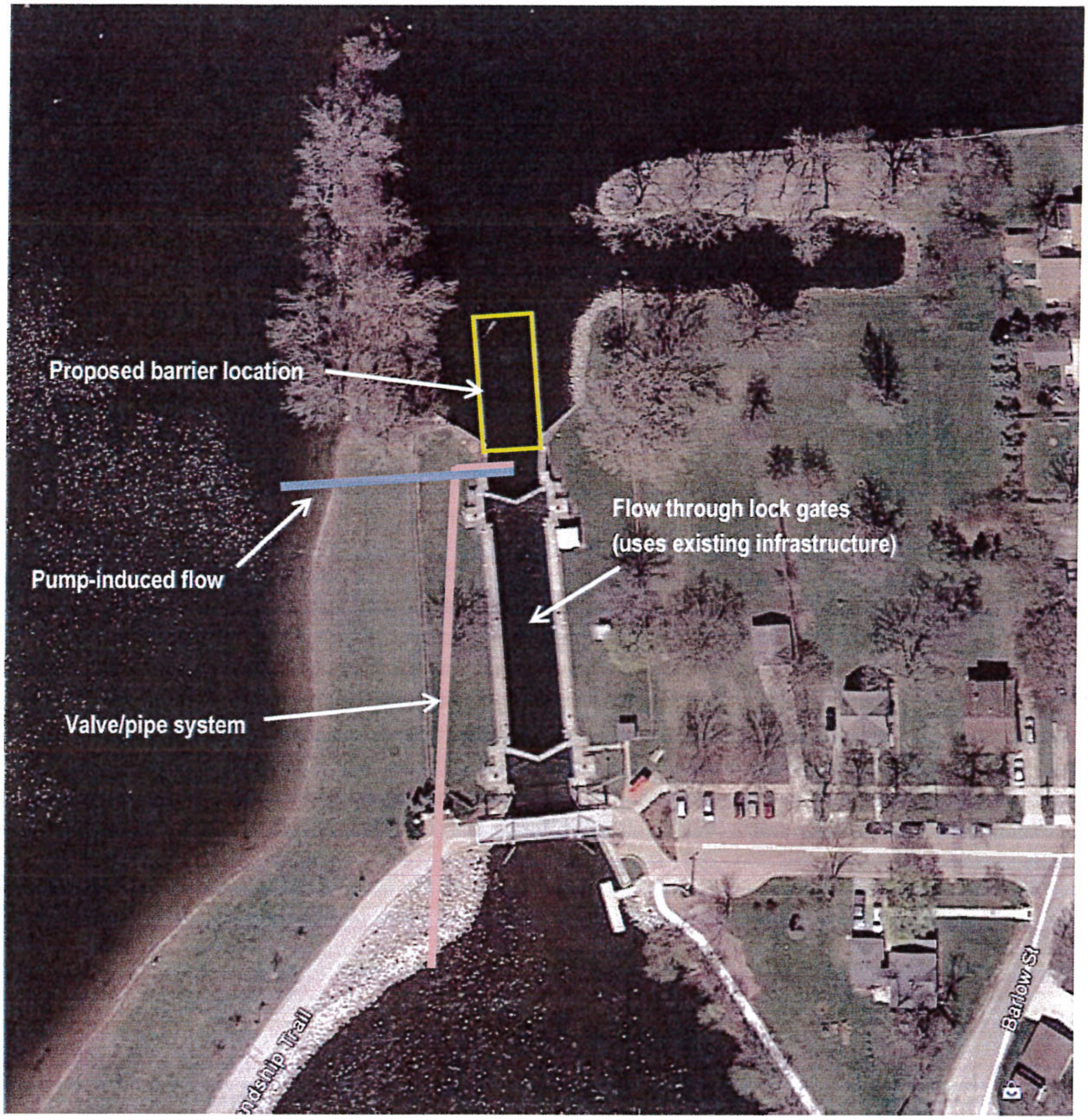


Figure 24. Potential locations/alignments of velocity inducement systems (Source: Google Earth).

The target duty cycles presented for each configuration in the Results section represents assumptions on the waveform required to deter fish. Nine species have been identified as restricted or prohibited from upstream migration into Lake Winnebago (Table 1). As presented previously in this report, the only invasive fish species that is currently present in the Fox River is Round Goby. Research on the effective waveforms and voltage gradients that deter Round Goby have been performed (Savino et al. 2001, McLaughlin and Phillips 2005), and based on this research the indicated duty cycle for a benthic fish-only barrier (Configuration 1) is 4%.

The same research has not been done for many of the other species in Table 1, however. The most common groupings of fish for such research are families Cyprinidae (carp) and Salmonidae (salmon and trout). Grass Carp is in family

Cyprinidae and deterrence settings are well-known for this species. In general, the settings to deter both Cyprinidae and Salmonidae are fairly similar, but they are not always similar for all fish. For example, Smith-Root has conducted studies on electrical settings for deterrence of Sea Lamprey, and preliminary findings are that the required pulse frequency and duty cycle is higher than those values needed to deter carp and salmonids. Information needed to determine deterrence settings for the other species in Table 1 simply does not exist at this time. It is possible to make assumptions – for example Round Goby and Eurasian Ruffe are both in Order Perciformes – but physiological differences and environmental differences may mean their individual responses to electrical fields are very different.

The best way to determine the individual responses of each species to electric fields is to determine them experimentally, such as a flume study. This may not be economically feasible or even desired by FRNSA or Wisconsin DNR until such time as these fish find their way into the Fox River. In the case an invasion occurs, the electrical settings that deter the fish can be experimentally determined and the electrical barrier equipment changed or augmented, if needed, to project the effective deterrent electric field at Menasha Lock. With this knowledge forthcoming, the electrical barrier can be designed to respond to the imminent threat(s) in the Fox River, which currently happens to be Round Goby.

Both the Results and Recommendations sections utilizes this assumption, but rounds up the duty cycle from 4% to 5% as existing electric barriers that are designed to deter species in families Cyprinidae and Salmonidae typically have duty cycles of 2-5%. The assumed target voltage is 2.54 V/in, the target experimentally determined for Round Goby as discussed earlier in this report. (This target voltage is not substantially higher than the deterrent gradients determined for most adult salmon and carp.) Smith-Root considers these to be reasonable assumptions for a feasibility study and acknowledges that increased migration pressure from Sea Lamprey – and possibly other species in Table 1 for which responses to electrical fields are currently unknown – may lead to a requirement to upsize the power output capacity of the pulse generating equipment in order to achieve deterrence.

In addition to the configurations presented in this report, Smith-Root considered a layout that incorporates the electric barrier fully inside the Menasha Lock chamber. This layout was deemed infeasible within the constraints desired by FRNSA for the following reasons:

- An electric barrier inside the Menasha Lock chamber would need to be "on" at all times;
- The electrical field creates a step potential (shock hazard) for boats that are tied to the cleats;
- Panels made of dielectric material (such as PE or PVC) would be required to be installed on the walls and floor of the lock, narrowing the lock chamber width; and
- The panels and electrodes would need to be installed to above the Lake Winnebago water line and would be visible at all times.

A different style of electric barrier, referred to as a "sweeping barrier," could possibly be located in the Menasha Lock chamber. The sweeping barrier would be off until the lower lock gate is opened. This style of electric barrier allows fish to enter the lock but "sweeps" them out with a deterrence field that gradually migrates downstream within the lock and to the outside the of lower lock gate. Advantages of this type of design is that the barrier could be turned off when the lower lock gate is closed, and the electrodes only need to be installed to the maximum level of Little Lake Butte Des Morts. This type of system is conceptual at this time, however, and no current sweeping field electric barriers are currently in operation.

RECOMMENDATIONS

Based on the discussion in the previous section, Smith-Root believes that the deterrent systems described in Configurations 1, 3, and 4 will provide the most effective deterrence to upstream migration of fish. Configuration 1 only focuses on the bottom few feet of the water column for benthic adult Round Goby, while Configurations 3 and 4 presents a deterrent electric field to the entire water column. The selection of the applicable configuration is a policy decision to be made by FRNSA with input from state and federal agencies.

The configurations are also quite different in terms of capital cost and operational cost. Configuration 3 requires a larger concrete structure than Configuration 1. Configuration 4 requires installation of dielectric coatings or panels on the existing lock walls, lower lock gate, and outlet wingwalls. The power output demand for Configuration 1 is significantly lower than that for configurations 3 and 4.

It is possible to construct an electric barrier infrastructure that can support the barrier in Configuration 3, but to build the electrodes and operate the barrier initially to deter Round Goby as described in Configuration 1. This "compromise" may effectively balance operational cost and human safety with the need to protect against upstream migration of fish that are present in the Fox River now and in the future. A similar arrangement may be possible for Configuration 4 as well.

This section will present an estimate of equipment required to produce the minimum voltage gradient fields for configurations 1, 3, and 4. Table 2 summarizes required and optional equipment.

Equipment

Pulse Generators

Smith-Root pulse generators produce the pulsed signal that is transmitted through cable to the mild steel electrodes. The pulsers produce the electrical field that is conducted into the barrier structure at the selected deterrent voltage gradient of 2.54 V/in.

For Configuration 1, the power needed to produce a deterrent voltage gradient at 4% duty cycle is 840 W when water conductivity is 509 µS/cm. Peak current is 8 amps in this scenario. To produce these electrical output settings, one (1) Smith-Root BP-1.5 POW pulse generator is required.

For Configuration 3, the power needed to produce a deterrent voltage gradient at 5% duty cycle is 14.0 kW when water conductivity is 509 µS/cm. Peak current is 6.9 amps in this scenario. To produce these electrical output settings, ten (10) Smith-Root BP-1.5 POW pulse generators are required.

For Configuration 4, the power needed to produce a deterrent voltage gradient at 5% duty cycle when water conductivity is 509 µS/cm is 1.4 kW when only the downstream segment is on, and 11.3 kW when the entire barrier is on during lockage operations. Peak current is 3.2 and 7.4 amps in these scenarios, respectively. To produce the maximum electrical output, eight (8) Smith-Root BP-1.5 POW pulse generators are required, though fewer pulse generators would be needed to power the downstream-only electric field.

For all configurations, one (1) spare BP-1.5 POW pulse generator is recommended as an on-site backup. Larger custom pulse generators can be manufactured that will produce the full range of output.

Electrodes

Please note that electrodes are not typically Smith-Root supplied equipment. They are made from common mild steel stock and typically are construction line items.

For Configuration 1, the recommended electrode layout is (17) parallel 2-inch by 1-inch steel bars spaced 2 feet apart on center. The electrode material should be uncoated mild steel (A36 or other grades). The lengths of each electrode should reach across the bottom of the channel – 35 feet. These electrodes are relatively uncomplicated for a steel mill to fabricate; smaller sections can be welded together in the field for ease of transport and handling.

The electrode layout for Configuration 3 is seven (7) parallel 4-inch by 1-inch steel bars spaced 6 feet apart on center. Electrodes should reach to the top of the barrier wall (12.3 feet on each side), so the total length of each electrode should be nearly 50 feet. Electrode sections can be welded together in the field for ease of transport and handling. The electrode material should be uncoated mild steel (A36 or other grades).

The electrode layout for Configuration 4 is seven (7) parallel 4-inch by 1-inch steel bars spaced approximately 10.5 feet on center. The electrodes should reach to the the top of the expected Little Lake Butte Des Morts water level (12.3 feet on each side). The 17.5-foot long concrete structure on the downstream side of the wingwalls should be constructed to this elevation. The elevation of the tops of the existing wingwalls should be evaluated to determine if they reach this water level. In the lock structure, the electrodes do not need to reach to the top of the existing walls, as fish will not be able to traverse into the lock when water levels match Lake Winnebago. Thus, the tops of the electrodes in the lock structure only need to extend 12.3 feet above the bottom of the lock. Each of the upstream four electrodes will be 35 feet across and measure a total of about 50 feet each. The downstream three electrodes are of different lengths as they meet the diagonal wingwalls at different locations. The electrode material should be uncoated mild steel (A36 or other grades).

Location of Deterrent System Equipment

The deterrent system control equipment should be housed inside a secure, climate-controlled, weatherproof structure that is resistant to insect infestations. Heating and air conditioning units should be installed to maintain normal operating temperatures inside the control building/enclosure. An existing structure on the northeast end of the lock may be able to be retrofitted to house the barrier control equipment. Alternatively, a new control building can be constructed for this purpose; in this case the building should be constructed as close to the barrier as possible, preferably within 100 feet of the end of the array to minimize voltage drops from long delivery cables. For Configuration 1, the fewer number of pulse generator units make it feasible to construct a smaller enclosure instead of a building for the control equipment.

Controls

The proposed deterrent system configuration produces a synchronized, pulsed DC electric field. Pulse frequency, voltage, waveform shape and duration can be modified to optimize operation and fish behavioral response. Monitoring and adjustments can be made remotely through the control equipment via broadband internet. To facilitate multiple signal communications and remote communications and monitoring, both configurations include one (1) FBTCS integrated into the pulse generating equipment.

Backup Power

In the event of a power outage, the electrical deterrent system will not operate unless a backup power system is included. Smith-Root barriers that serve critical purposes include backup power equipment including a generator, fuel tank or fuel supply, and automatic transfer switch. In addition, a UPS can be installed that provides battery power during the "gap period" between the power outage and the start-up of the generator. Whether a backup power system is used is a decision to be made by the owner/operator. A backup generator, fuel tank, automatic transfer switch, and UPS battery are included in the buy-in equipment list in Table 2.

Safety

For more than 50 years, Smith-Root has produced controlled electric fields in water for the purpose of manipulating the physiological behavior of fish. Smith-Root equipment is regularly used to sample endangered and threatened fish species, therefore fish health and safety is paramount in the design of Smith-Root products which minimize the risk of harm while maintaining effective physiological manipulation. Similar principles that apply to understanding electric thresholds and responses in fish also apply to understanding thresholds and responses for accidental exposure of humans to these electric fields. Therefore, all Smith-Root electric systems are designed with precautions for human safety as a primary concern. Thousands of portable Smith-Root electrofishing units (backpack, boat, shore, etc.) have been used safely since the 1960s by governmental agencies, private consulting firms and universities. Further, more than 65 Smith-Root electric barriers are in operation across the globe without a single incidence of human harm.

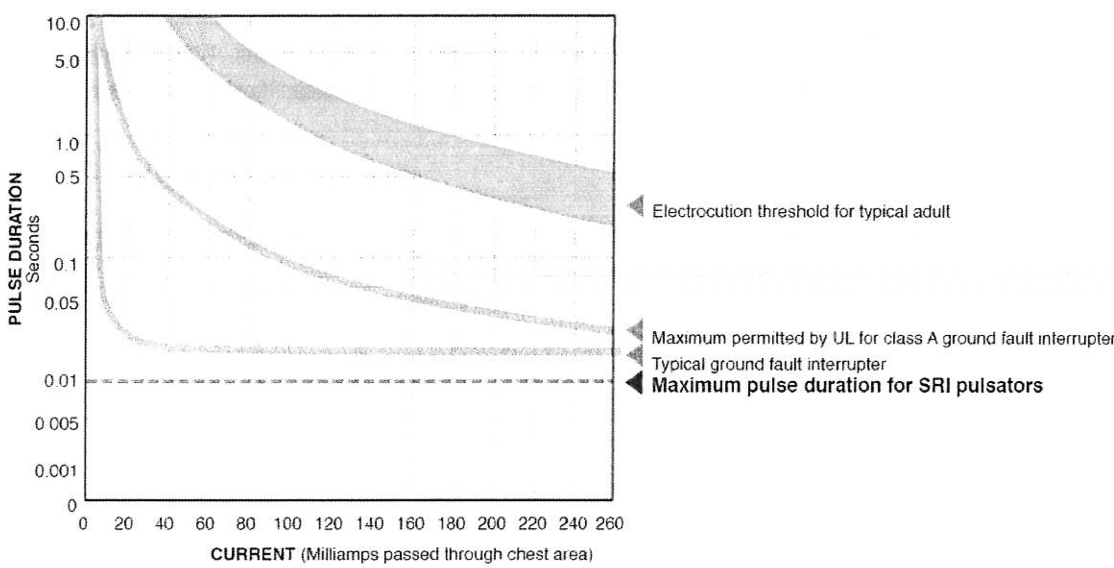
There are inherent risks to human health and safety associated with all waterway environments, many of which are similar to those that would exist in a waterway with an electric barrier. In order to maintain a safe waterway, it is critically important that waterway users have an understanding of safe behavior, are educated and notified of potential risks and that proper safety measures are in place to respond to an emergency. For example, individuals working around extremely cold water are made aware of inherent risks and appropriate responses to an emergency situation. Many of these risks and responses are similar to working around water that contains an electric field. In cold water, a man overboard scenario requires a swift response to remove a person from the water as quickly as possible to prevent injury. Further, it is important to prevent or minimize the exposure to the water of those performing the rescue. A similar response would be required from a waterway with an electric field, but with the added safety of knowing that unlike a cold water situation, the electric field is limited to a small defined area, and the electric field can be immediately shut down to allow for self-rescue and/or individuals to safely enter the water to assist with rescue without risk of being in the electric field. Simply being around potential dangers like cold water or an electric field in the water does not prevent boating operations in that environment; however, it does require a greater sense of safety awareness to minimize risk, and requires a greater understanding of safety protocols from those regularly operating in and around the environment of concern.

To increase safety of electric barriers, Smith-Root designs electric fields to balance the use of settings that minimize potential harm while achieving the objectives of the project. The selection of multiple factors, including pulse frequency (Hz), type of current (Smith-Root exclusively uses pulsed direct current – DC – for its electric deterrent systems instead of straight DC or alternating current – AC), duration of exposure (time), and current (amps), can contribute to potential risk of harm when exposed to an electric field. It is impossible to design an electric barrier that has a small electric field which poses zero threat to human safety while at the same time generates an electric field which is large enough to deter fish passage. Some risks will have to be accepted with respect to safety in order to accommodate the goal of preventing upstream passage of fish.

Waveform and Human Thresholds

Smith-Root fish barriers and guidance systems are designed to be non-lethal and to use only pulsed direct current (DC) to create electric fields. Humans are three times more likely to be harmed by alternating current (AC) than by DC, and it has been shown repeatedly in the scientific literature that use of AC can injure fish. Pulse frequency, duration and current can all contribute to potential harm; therefore SRI sets these values well below the electrocution threshold of a typical ground fault interrupter. Figure 25 illustrates the typical barrier pulse strength versus other known thresholds. The graph shows that the typical electrocution threshold for humans begins at around 200 ms (0.2sec) pulse width (duration). Smith-Root pulse generators typically utilize durations in the 2-3 ms range. From this analogy, the Smith-Root pulsers maximum pulse width is approximately 66 to 100 times less than the electrocution threshold.

Smith-Root electric fish barriers and deterrence/guidance systems are designed to dissipate voltage over the length of the field so that the voltage gradient over any small length of the field is much less than the total voltage applied. Humans who accidentally enter the electric field are not exposed to the total voltage potential for which the barrier is designed. In any case, Smith-Root recommends that people recreating or working near the fish barrier wear a personal flotation device to ensure floatation should they fall into the water.



Effects on humans of an electrical pulse passed through the chest area.
Adapted fromThe Handbook of Electronic Safety Procedures. Edward A. Lacy. 1982 edition

Figure 25. Maximum pulse width of Smith-Root pulsers compared to electrocution threshold pulse width for a typical adult human.

Site Access and Security

The layout of Menasha Lock currently restricts public access to the proposed location of the electric barrier by land, but allows free access by water. While allowing fishing is not a recreational objective of the lock, Smith-Root's experience at other electric deterrence systems has demonstrated that a concentration of fish immediately downstream of the barrier can attract anglers.

It is recommended that signage and education should be utilized to inform land and water users of the hazards associated with the deterrent system. Signage can be affixed to posts on the land and also on buoys in Little Lake Butte Des Morts immediately downstream of the barrier. Informational kiosks can be built near the lock and at the excavated boat access channel adjacent to the lock. Community education, in the form of meetings or literature, can be created and distributed to boaters that utilize the lock. A warning light can be illuminated when the barrier is operating to notify water users of the hazard.

Various Smith-Root electric fish barriers have incorporated patrolling security and/or video surveillance. These strategies may be employed for safety and security reasons.

Emergency Power-Off Switch

An emergency power-off switch could be installed near the electrical deterrent system (and possibly within the secured/fenced area at the lock) to allow an operator to quickly disable the barrier. This switch would be wired directly to the electric output of the barrier and immediately stop the flow of electricity to the electrodes. A recommended switch style is a simple, large, red push button type of switch that is covered by a hinged clear Plexiglas or plastic bubble to limit accidental deployment.

Summary of Configurations

Table 2 summarizes the recommended equipment for the Menasha Lock electrical deterrent system configurations. Smith-Root equipment and selected buy-in equipment are presented in the table.

Table 2. Barrier system equipment recommendations.

Configuration 1: Exclusive Benthic Fish Barrier	Configuration 3: Graduated Field Fish Barrier	Configuration 4: Graduated Field Fish Barrier that Spans the Lower Lock Gate
	Smith-Root Equipment	
(2) 1.5 kW POW Pulse Generators (includes 1 spare)	(11) 1.5 kW POW Pulse Generators (includes 1 spare)	(9) 1.5 kW POW Pulse Generators (includes 1 spare)
(1) FBTCS communication system with OPTO-22 programmable output controller	(1) FBTCS communication system with OPTO-22 programmable output controller	(1) FBTCS communication system with OPTO-22 programmable output controller
	Buy-in Equipment, Not Included in Cost Estimate	
(17) uncoated mild steel (A36 or similar) electrodes, 2-inch by 1-inch, each with approximate total length of 35 feet	(7) uncoated mild steel (A36 or similar) electrodes, 4-inch by 1-inch, each with approximate total length of 50 feet	(7) uncoated mild steel (A36 or similar) electrodes, 4-inch by 1-inch, with approximate total lengths of 50 to 119 feet
Locomotive Cable 2000V	Locomotive Cable 2000V	Locomotive Cable 2000V
Small building/shed or weatherproof enclosure to house equipment (if existing building is not retrofitted)	Small building/shed to house equipment (if existing building is not retrofitted)	Small building/shed to house equipment (if existing building is not retrofitted)
Climate control equipment	Climate control equipment	Climate control equipment
Safety signage	Safety signage	Safety signage
Various connectors and fasteners	Various connectors and fasteners	Various connectors and fasteners
	Optional Equipment, Not Included in Cost Estimate	
	Backup generator	
	Fuel tank (alternatively, connection to fuel supply line)	
	Automatic Transfer Switch for generator	
	Uninterruptable Power Supply (UPS) battery	
	Depth sensor	

Estimated System Costs

The estimated partial cost includes the following:

- Equipment and start up;
- Operating cost; and
- Maintenance agreement.

Cost to construct is not included in this feasibility study report. This includes some items that are not supplied by Smith-Root and should be estimated by the owner or contractor. Examples of such items are presented in Table 2.

The costs provided in this section are valid for 60 days from the date of the report.

Equipment Cost Estimate

The following reflects Smith-Root's pricing for 2017. Costs for labor and equipment, as well as for expenses such as travel, are subject to change in the future no less than the prevailing cost of inflation. Costs are quoted in United States Dollars.

The Smith-Root equipment estimate for Configuration 1: ***Exclusive Benthic Fish Barrier*** includes the following:

1. (2) 1.5 kW POW pulse generators (includes 1 spare)........$ 51,970.00
2. (1) FBTCS/OPTO-22 Communications System........$ 28,506.00
3. Safety signage (estimate, to be developed)........$ 2,000.00
4. Shipping of Smith-Root equipment to site........$ 860.00
5. Smith-Root staff travel and labor for: ....$ 18,839.00
   a. Operations and maintenance manual
   b. Installation of Smith-Root hardware (2 staff, 1 day on site, 2 days travel)
   c. On-site training of guidance system operations and maintenance (1 staff, 1/2 day on site, travel inclusive in above item)

Estimate of Smith-Root supplied equipment and labor........$ 102,175.00

Estimate of Smith-Root engineering design, specifications, and construction cost estimate........$ 92,000.00

The Smith-Root equipment estimate for Configuration 3: ***Graduated Field Fish Barrier*** includes the following:

1. (11) 1.5 kW POW pulse generators (includes 1 spare)........$ 285,835.00
2. (1) FBTCS/OPTO-22 Communications System........$ 28,506.00
3. Safety signage (estimate, to be developed)........$ 2,000.00
4. Shipping of Smith-Root equipment to site........$ 1,290.00
5. Smith-Root staff travel and labor for: ....$ 18,839.00
   a. Operations and maintenance manual
   b. Installation of Smith-Root hardware (2 staff, 1 day on site, 2 days travel)
   c. On-site training of guidance system operations and maintenance (1 staff, 1/2 day on site, travel inclusive in above item)

Estimate of Smith-Root supplied equipment and labor........$ 336,470.00

Estimate of Smith-Root engineering design, specifications, and construction cost estimate........$ 99,000.00

The Smith-Root equipment estimate for Configuration 4: ***Graduated Field Fish Barrier that spans the lower lock gate*** includes the following:

1. (9) 1.5 kW POW pulse generators (includes 1 spare)..$ 233,865.00
2. (1) FBTCS/OPTO-22 Communications System..$ 28,506.00
3. Safety signage (estimate, to be developed)..$ 2,000.00
4. Shipping of Smith-Root equipment to site..$ 1,290.00
5. Smith-Root staff travel and labor for: ....$ 18,839.00
    a. Operations and maintenance manual
    b. Installation of Smith-Root hardware (2 staff, 1 day on site, 2 days travel)
    c. On-site training of guidance system operations and maintenance (1 staff, 1/2 day on site, travel inclusive in above item)

Estimate of Smith-Root supplied equipment and labor..$ 284,500.00

Estimate of Smith-Root engineering design, specifications, and construction cost estimate..................$ 110,000.00

Typical Monthly Operating Cost

Operating costs are determined by the amount of electricity used to power the deterrent system and the climate control requirements for the control building.

A basic calculation can be made to determine monthly costs for deterrent system operation. The assumption made for average electricity cost for operating the barrier is \$ 0.1144 / kWh[3]. The assumption for energy demand is the maximum output power plus 1.5 kW to account for control equipment and climate control.

For Configuration 1, the maximum level of power required to operate the deterrent system continually at peak voltage at 20% duty cycle and 509 µS/cm conductivity is approximately 2.4 kilowatts (including electricity to power the barrier and climate control equipment). Therefore, the maximum monthly power cost for operation, assuming continuous 24-hour per day operation during a 30-day month, is:

- \$0.1144 / kWh x 2.4 kW x 720 hours/month = \$197.68 maximum monthly cost.

For Configuration 3, the maximum level of power required to operate the deterrent system continually at peak voltage with maximum depth of 12.3 feet, 30% duty cycle, and 509 µS/cm conductivity is approximately 15.5 kilowatts (including electricity to power the barrier and climate control equipment). Therefore, the maximum monthly power cost for operation, assuming continuous 24-hour per day operation during a 30-day month, is:

- \$0.1144 / kWh x 15.5 kW x 720 hours/month = \$1276.70 maximum monthly cost.

For Configuration 4, the maximum level of power required to operate the deterrent system continually at peak voltage with maximum depth of 12.3 feet, 5% duty cycle, and 509 µS/cm conductivity is approximately 12.8 kW (including electricity to power the barrier and climate control equipment). However, the peak power output would only occur a fraction of the time in this scenario. An assumption is made that over the course of a typical month, the maximum output of 12.8 kW occurs

[3] Menasha Utilities Rate File. Effective November 1, 2013. Accessed on 8/18/2017: http://apps.psc.wi.gov/vs2010/tariffs/viewfile.aspx?type=electric&id=3560. Energy cost based on "General Service" category; Customer Charge and Power Cost Adjustment may also be applicable to monthly cost.

5% of the time, and the rest of the time the output is 2.9 kW. With this assumption, the maximum monthly power cost for operation, assuming continuous 24-hour per day operation during a 30-day month, is:

- $0.1144 / kWh x 2.9 kW x 720 hours/month = $238.87 for 95% of the month = $226.92
- $0.1144 / kWh x 8.8 kW x 720 hours/month = $1,054.31 for 5% of the month = $52.72
- Total is $279.64 maximum monthly cost.

These estimates reflect the maximum possible monthly cost using Menasha Utilities "General Service" rates; higher or lower rate categories and extra fees may apply. Monthly cost will be lower if the barrier is not operated continuously. When water depth and conductivity values are lower, the pulsers will operate at a lower power output, substantially reducing the monthly cost of operation.

Assumptions and Exclusions

The following are Smith-Root's major assumptions and exclusions for the project:

- The feasibility study models and calculations were without a detailed hydraulic model. Actual deterrent system performance may vary if the assumed physical and water quality conditions differ substantially from the assumed conditions;
- Inducing a velocity through the electric barrier may be desirable or required for operation of a barrier. Detailed feasibility of velocity-inducing strategies is not included in this report and estimated costs are not provided;
- Design and the power consumption estimate assumes freshwater with ambient conductivity of 509 µS/cm;
- The calculation of required power output is related to the target voltage gradient and duty cycle of the output, which in turn is dependent upon the target fish and species for which deterrence is desired. At this time the target species is Round Goby, and for all calculations (except for Configuration 1) the assumption is that the entire water column is protected, meaning the deterrence electrical field is presented at the water surface and throughout the water column. It is anticipated that this target voltage gradient and duty cycle will be sufficient to deter other species on Wisconsin DNR's list of invasive fish in Fox River, particularly Grass Carp, but it is unknown if it is sufficient for all other species. Deterrence of Sea Lamprey would likely require a different waveform than assumed for Round Goby that would necessitate an increase in output duty cycle.
- The barrier equipment should be housed in a climate controlled building or enclosure. The building/enclosure should be secure from public access and should be sufficient for protection of the equipment from excess heat and cold, humidity, flood, and insect infestation. The decision of whether to construct a new building, a new enclosure, or retrofit an existing building adjacent to the lock is not assumed in this document and costs have not been estimated for this task.
- Backup power, including generator and outage gap protection, is not specified in this feasibility report or cost estimate; and
- The costs of obtaining environmental and construction permits, and of communication and collaboration with USACE and Wisconsin DNR, have not been estimated in this report. Similarly, required permits and submittals have not been identified.

Maintenance

Electrodes

The mild steel electrodes are subject to environmental corrosion, a condition which can be exacerbated by the pulsed DC electrical field. The effects on the electrodes are somewhat similar to electrolysis, where ions from one surface are transferred to another. As such, the electrodes do not corrode at the same rate, and some electrodes may need replacement sooner than others.

A rough estimate of electrode life was prepared for the electrodes in the two configurations described above. Some of the new electrodes, if installed with the dimensions specified previously, operated with the indicated currents and duty cycles, would take about 20 years to lose 60% of their mass, while others would take longer to reach this level of corrosion. It is likely that some electrodes in an electrode array would take less time to reach the 60% loss of mass milestone at which replacement is recommended, and other electrodes would take longer. Electrode life would decrease if the duty cycle is increased over the 4% (Configuration 1) or 5% (Configurations 3,4) settings described in this report. Please note that the electrode life estimate does not take into account environmental corrosion.

Maintenance Agreement Estimate

Smith-Root manufactured deterrent system equipment is covered under a one (1) year Limited Product Warranty. During the one (1) year warranty period, Smith-Root's technical team electronically and remotely monitors the deterrent system, provided connectivity is available and the FBTCS is connected to the system. Smith-Root's mission is to resolve any noted issues, and field any questions or concerns the client might have in a timely manner.

For coverage beyond the one (1) year warranty period, Smith-Root offers a service/maintenance contract. Provided for reference is a list of sample services that are included.

- Array Tests
- Pulser Tests
- Fish Barrier Telemetry and Control System Tests (if FBTCS is connected to system)
- Incoming Power Supply Tests
- Auxiliary Generator Tests (if auxiliary generator and FBTCS are connected to system)
- Equipment Building Checks/Review
- Reports
    - Deterrent System Inspection Report
    - Site Alarm History Printout and Analysis (if FBTCS is connected to system)

Within the Smith-Root service/maintenance contract, inspections are typically completed on an annual basis (but could be done as frequently as quarterly) to test the deterrent system equipment and ensure a suitable electric field is being generated to adequately deter the target fish species. If the FBTCS is connected to the system, the site is remotely monitored and problems can be resolved by Smith-Root technicians with remote software changes; otherwise, replacement equipment can be specified for installation by trained technicians. For problems that cannot be addressed remotely, or are outside of the understanding of trained technicians, emergency site visits can be conducted by Smith-Root or its agents to resolve site issues in a timely manner.

Although no professional certification is required to maintain or adjust the settings or equipment at an electric barrier, training of owner-designated technicians is absolutely essential to ensure the proper operation of the system and the safety of site personnel.

Annual service for the site after the one year warranty period is over has been estimated at approximately **$11,500.00.** The estimate may vary based on current billing rates, travel expenses, etc. Service and monitoring pricing would be included in a separate contract.

CONCLUSION

Smith-Root performed a study of the feasibility of electrical deterrence of Round Goby and other invasive fish species at Menasha Lock. The study considered four configurations of deterrent systems at two locations: three configurations were positioned downstream of the lower lock gates, and one configuration spans the lower lock gate so that the barrier is downstream of the lock and in the lower segment of the lock. One of the four configurations was designed to exclusively deter benthic fish like Round Goby, while the other configurations address fish that utilize the entire water column for migration. All configurations use Smith-Root custom pulse generating equipment to deliver the electrical field to the barrier. The benthic-only configuration creates a uniform deterrent electrical field immediately above the barrier, as does the configuration that delivers a static field to the entire water column. A third and fourth configurations delivers a graduated electrical field to the water column, with a lower voltage gradient on the downstream segments of the barrier and a higher gradient on the upstream segments.

Smith-Root recommends either the exclusive benthic fish barrier or one of the two Graduated Field Fish Barrier (Configurations 1, 3, and 4) for further consideration by Fox River Navigational System Authority. Configurations 1 and 3 require a 35-feet wide concrete sill with vertical walls to be constructed downstream of the lock; the height of the vertical walls differs by configuration. The exclusive goby barrier would utilize 17 smaller electrodes deployed on the concrete sill floor only, creating an electrical deterrent field on the bottom of the channel only. The voltage gradient would be very weak at the water surface in this scenario. The Graduated Field Fish Barriers in Configurations 3 and 4 utilizes 7 larger electrodes to impart a deterrence field to the entire water column. The electrodes and barrier walls would extend to the top of the maximum water surface elevation in Configurations 3 and 4, which for all scenarios is that for Little Lake Butte Des Morts (rather than the higher Lake Winnebago water surface). Electrical gradient would be higher at the bottom of the barrier, but sufficient for deterrence of fish in at the water surface. Electrical gradient would also be stronger on the upstream side of the barrier, allowing volitional movement of fish away from the downstream side of the barrier.

The major difference between Configurations 3 and 4 is the barrier layout. Configuration 3 is located downstream of the lock and assumes the construction of a narrow, 35-foot channel where the existing wingwalls are located. Configuration 4 does not modify the structure layout significantly but requires dielectric coating or panels to be installed on the lock walls, lower lock gate, and wingwalls. Electrical deterrence equipment would be housed in a new small building, enclosure, or retrofitted existing building near the lower lock gates or the electric barrier. The equipment requirement is dependent on the selected configuration; it also is possible to build the barrier infrastructure to accommodate the Graduated Field Fish Barrier to deter all species of invasive fish but operate only to deter Round Goby initially, with minor future modifications to meet deterrence needs for other species.

The US Army Corps of Engineers and Wisconsin Department of Natural Resources should have significant input in further development of the electrical barrier option as a required response to resuming lock operations in the future. In addition, the need for inducing water velocity through the barrier in order to minimize fish kills should be assessed in more detail.

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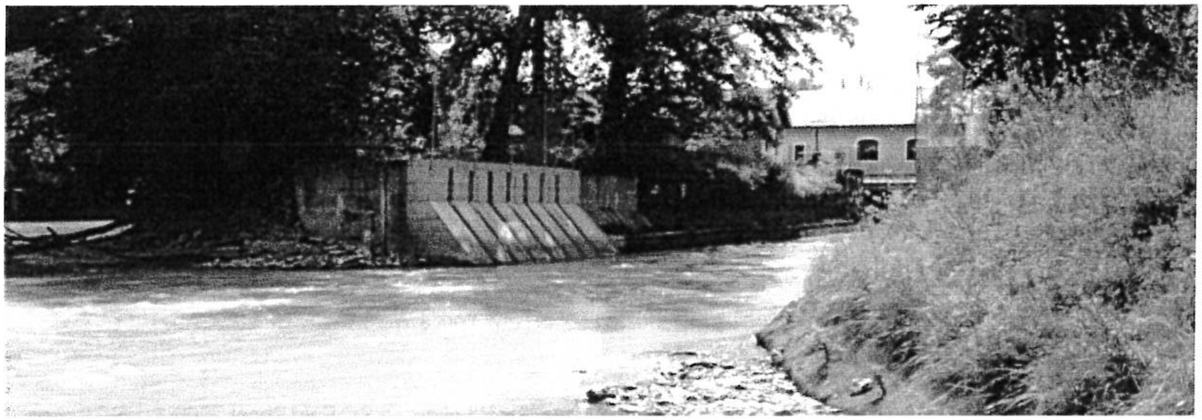
RELATED PROJECTS



Centrale Hydroelectrique de Vessy Tailrace Barrier

Geneva, Switzerland

Constructed in 2008

Smith-Root was engaged by Services Industriel de Geneva to design an electric barrier to prevent fish from the Arve River entering the Centrale Hydroelectrique de Vessy power station tailrace and becoming entrained in the low head turbine draft tubes.

The seven steel flat bar electrodes are sidewall and bottom mounted into an Insulcrete™ liner. Smith-Root's BP-1.5 POW European Union-certified pulsators provide the electric field. Construction was contracted by the owner from the Smith-Root drawings.

Following construction and commissioning of the barrier, a Swiss consulting firm was contracted by the hydropower station owner to conduct an independent study of effectiveness of the barrier system using 339 tagged trout. The study found no fish in the tailrace during the study period, and the tagged fish successfully guided fish to the main channel. Further, an "insignificant" number of untagged fish were encountered in the tailrace using electrofishing methods despite the availability of habitat in the tailrace.

Services Provided

- Civil, electrical, and mechanical engineering; hydraulic engineering
- Design of barrier electrodes and pulsers
- Software development and construction management

Site Characteristics

1.5 kVA POW	6	9.0 kW max.	1.2 m	10.1 m	Up to 1 m/s	240 µS/cm max.

Okoboji Lake Outlet Barrier

Spirit Lake, Iowa

Constructed in 2012

The primary objective of the Okoboji Lake Outlet Barrier is to prevent upstream migration of non-native carp into the Iowa Great Lakes. A secondary objective is to prevent outmigration of muskie, a stocked sportfish. The electrical barrier doubles as a physical barrier when water levels are low, and is very effective when water is high because maximum water depth typically does not exceed one meter over the barrier apron.

Through coordination with the United States Army Corps of Engineers (USACE) and Iowa Department of Natural Resources (DNR), Smith-Root performed the hydraulic, civil, structural, and electrical design to minimize erosion, sediment deposition, and friction losses, and most importantly to contain the 500-year flood event.

Smith-Root has implemented a safety management and educational plan in conjunction with Iowa DNR. Okoboji Lake Outlet Barrier provides visitors an insight into the requirements for such a device to keep the Iowa Great Lakes free of Asian carp. The site has a small parking area with warning signs and educational kiosks with opportunity for people to overlook the barrier.

Services Provided

- Electrical and electronic design of the pulsers and power supply systems
- Civil design of barrier and control building
- Supply of barrier equipment
- Construction oversight
- Regular maintenance

Site Characteristics

Pulsers	Pulser Qty.	Power Output	Water Depth	Waterway Width	Water Velocity	Conductivity
1.5 kVA POW	7	10.5 kW max.	1 m max.	50 m	0 – 1.1 m/sec	350 µS/cm

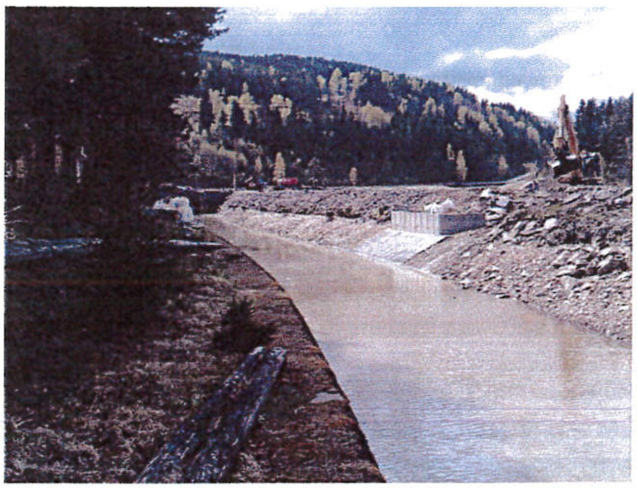
RYGENE HYDROPOWER TAILRACE BARRIER

Nidelva River, Helle, Norway

Client: Agder Energi

Constructed in 2014

Species: Atlantic salmon and arctic char
Barrier type: Upstream
Electrodes: Vertical steel cable electrodes fixed above and at the bottom.
Pulsators: (6) – 1.5kW (POW)



TELEMARK CANAL BARRIER

Kjeldal Lock, Norway

Constructed in 2012

Species: Northern Pike
Barrier type: Upstream
Electrodes: Flat bar steel electrodes installed over new Insulcrete layer.
Pulsators: (10) – 1.5kW (POW)

CLECO BARRIER

Mountain Bayou Lake, Louisiana

Constructed in 2011

Species: Grass Carp
Barrier type: Downstream, two (2) locations
Electrodes: Flat bar steel electrodes installed; one over Insulcrete base and the other over insulated fabric layer.
Pulsators: (6) – 1.5kW, each site (POW)

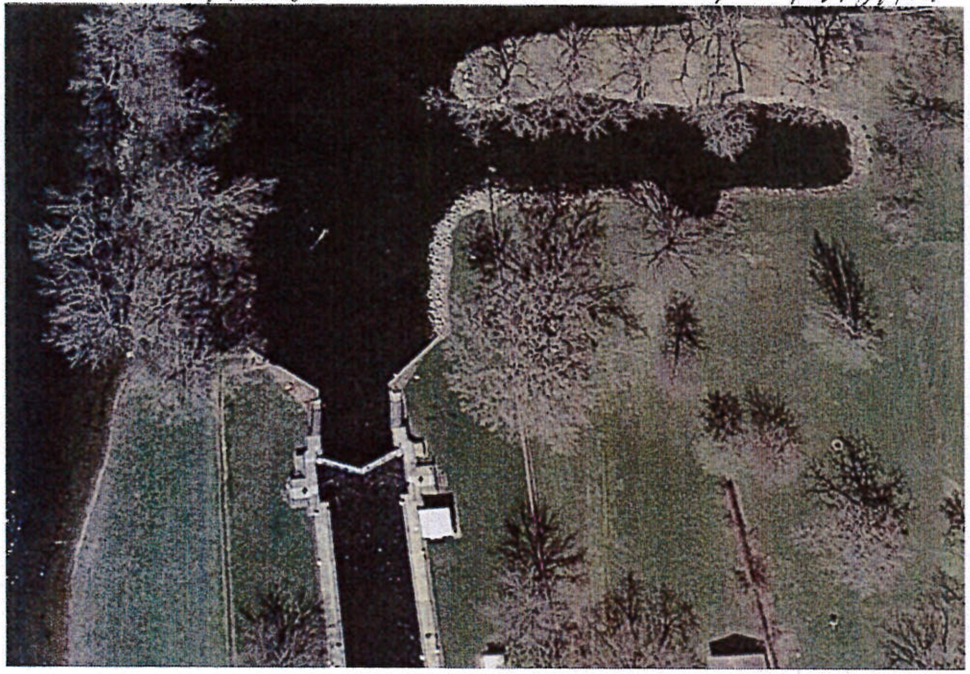
Smith-Root has more than 65 guidance arrays installed around the world. They meet the varying needs of natural resource agencies and private sector clients either to guide fish to desirable locations or to block them from accessing areas where they are not wanted.

To navigate to details for each of these sites please copy this link into your browser: http://www.smith-root.com/barriers/

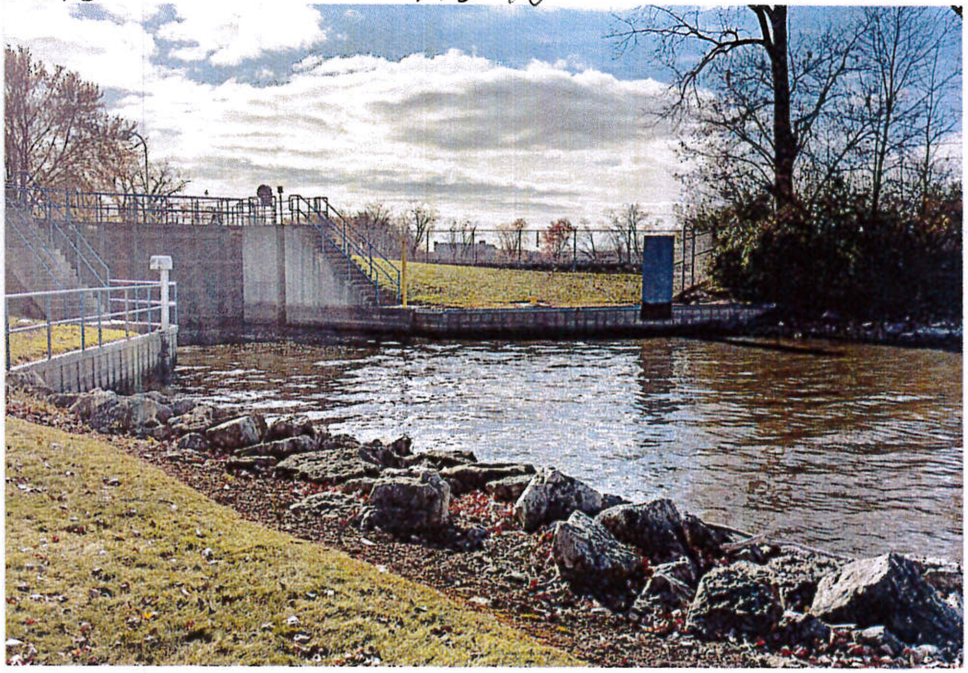
Once you are on the home page for Smith-Root fish barriers, look for a link in the white box near top of page for "Barrier Portfolio" next to the "Learn More" tab.

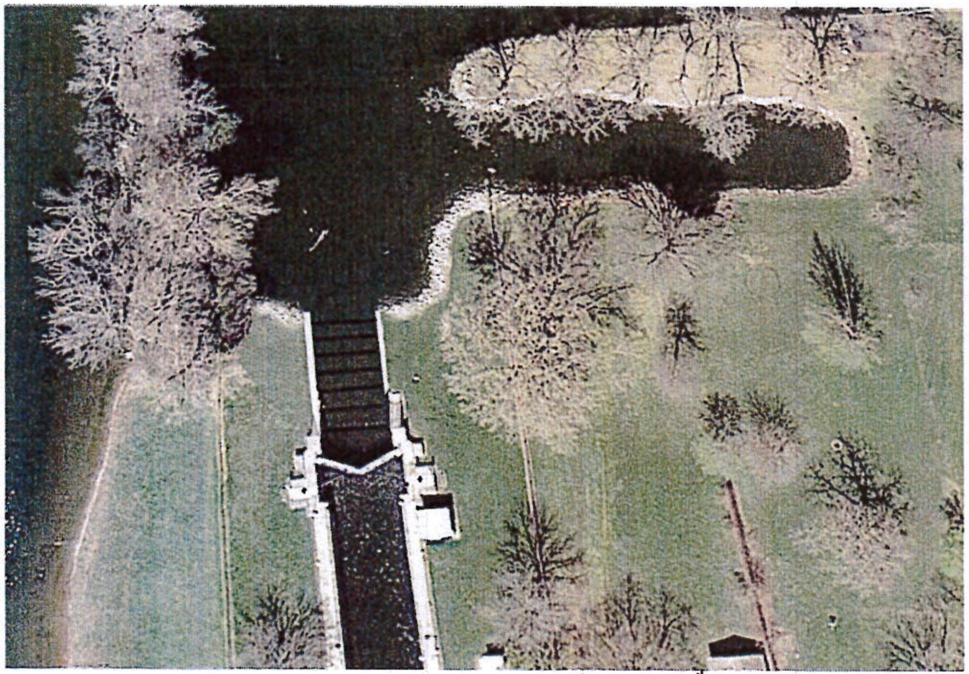
MOCKED UP VERSION
OF MENASHA LOCK

AS IS

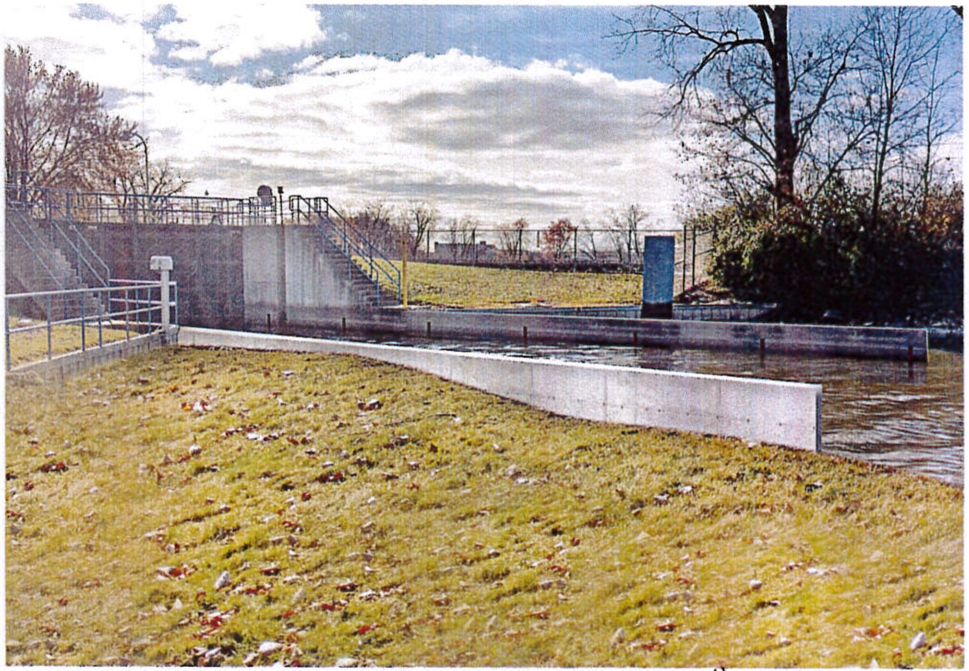


AS IS 2018



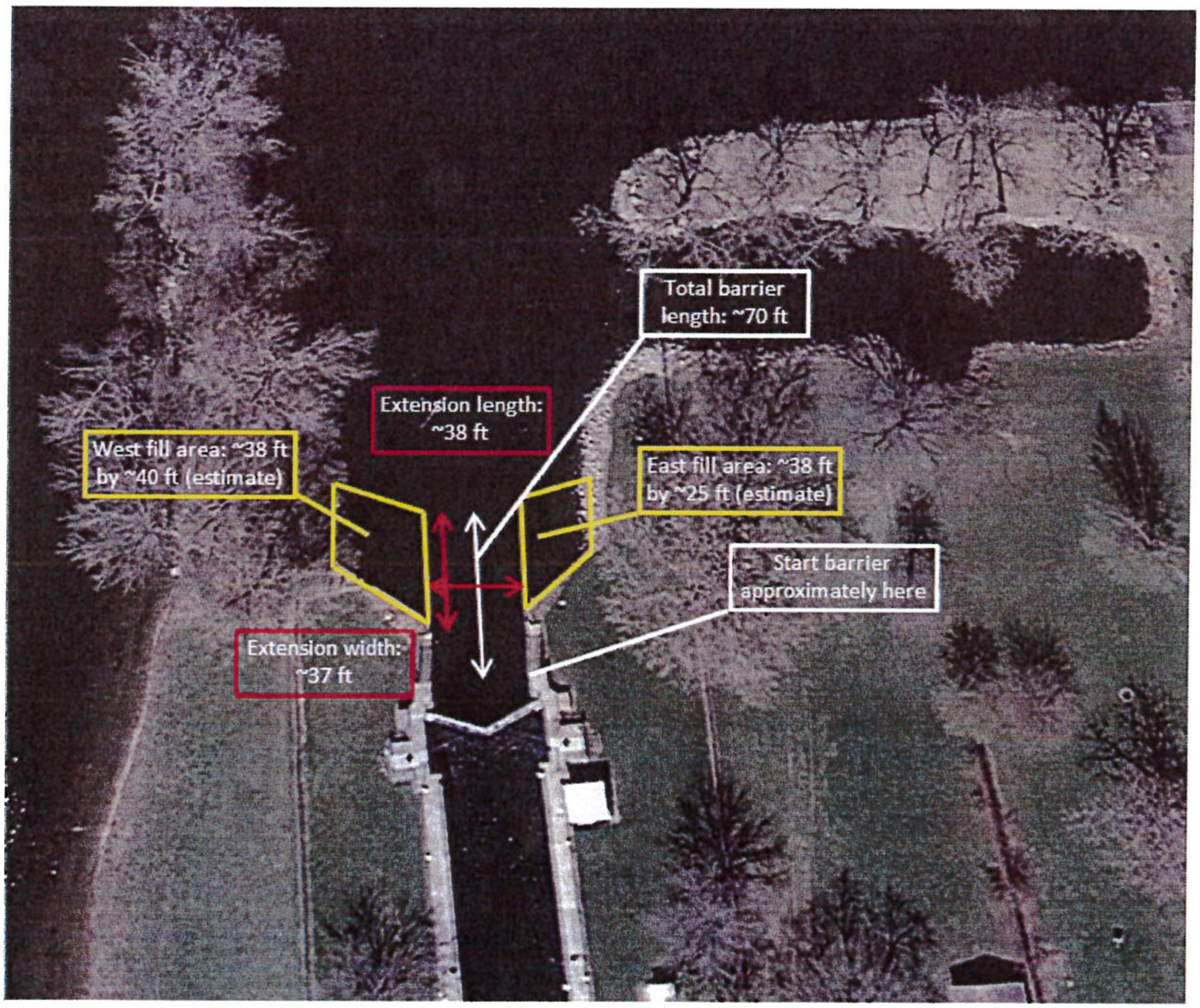


Shown w/Changes (Proposed)

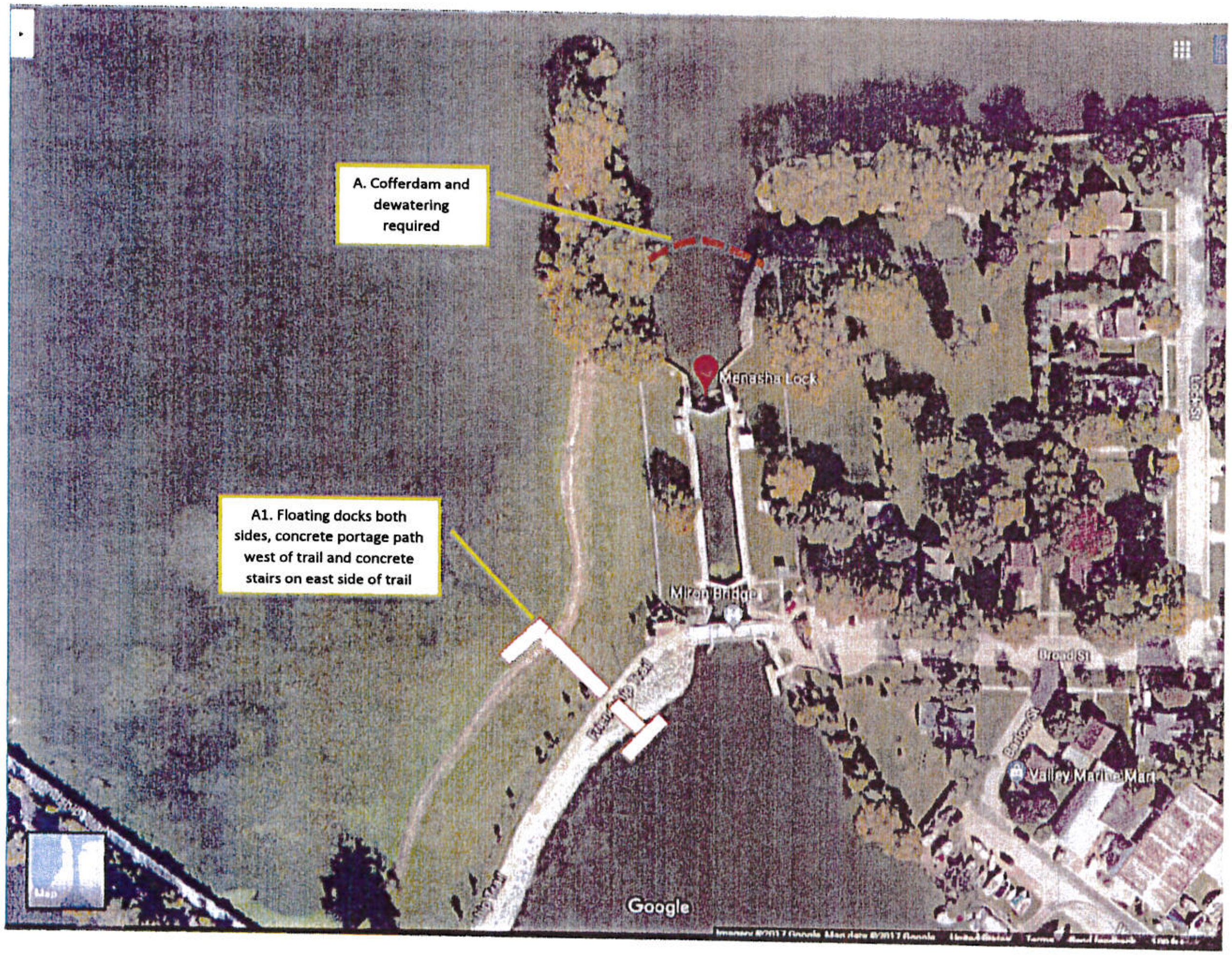


Show w/Changes (Proposed)

Construction Notes



Construction - NOTES



NOTES:

A. River channel has a silty/sandy bottom. Likely will be water concerns (more than pumping).

a. See existing drawing "Exist Menasha Lock 3_soils" for old soil borings

b. Include extra costs here. May need dewatering wells.

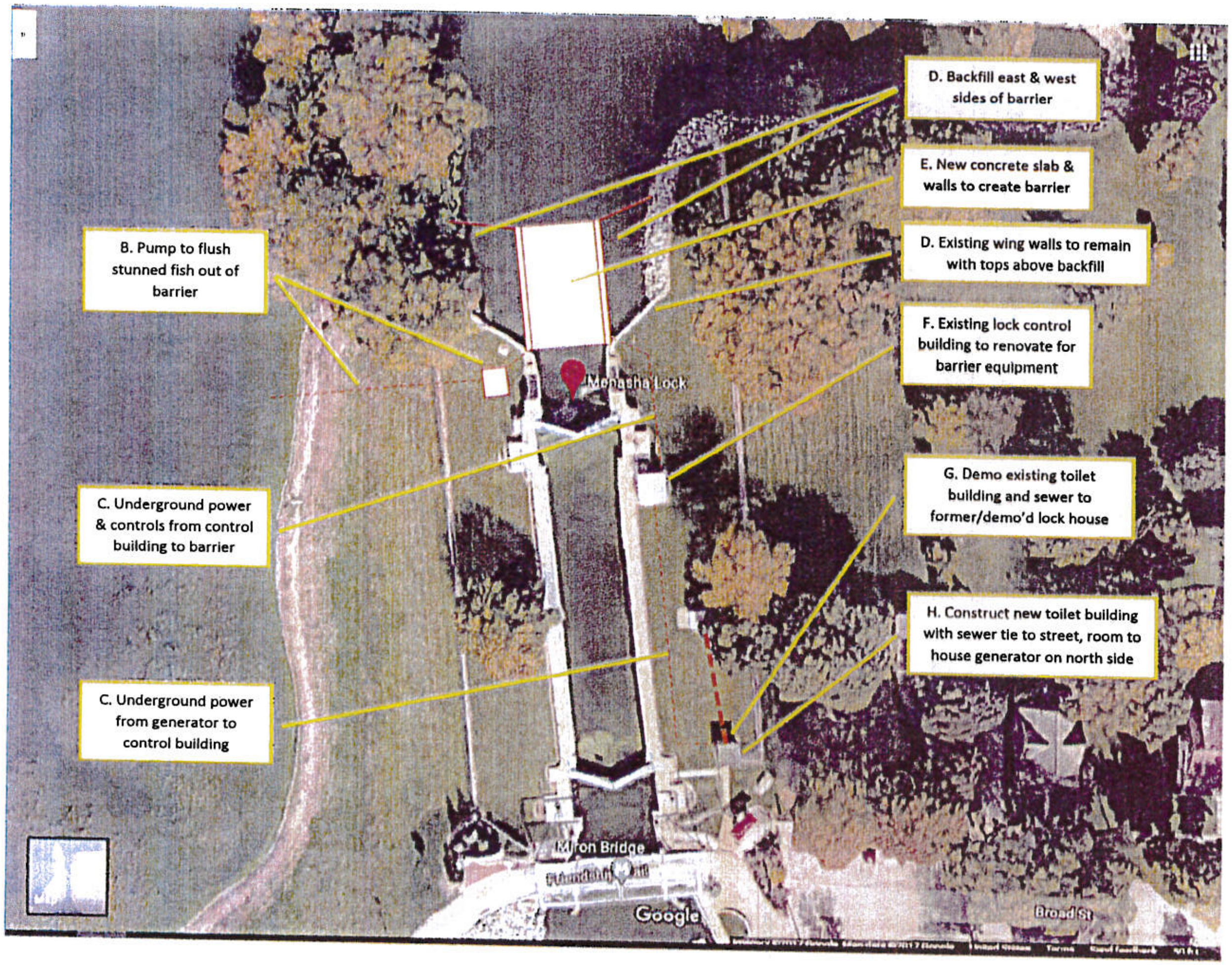
A1. Portage shall include:

a. (2) floating docks – Approximately 3' x 10'

b. Concrete path with stairs to east – 5'-0" wide, 6'-0"+/- elevation change, total length 33'-0" from path to water in plan.

c. Concrete path constructed of 4" thick x 5' wide x 80'-0" long concrete sidewalk. Likely will need to deal with PCB's if excavating here.

Construction Notes



NOTES:

B. For pump system to remove stunned fish from barrier, install hard piping underground with inlet or structure in Little Lake Butte des Morts. Water from Lake to be pumped across levee and into barrier. BDM has very silty bottom.

C. See "Exist Menasha Lock 10_chamber constr" drawing for cross section at lock walls. Original lock construction exists behind concrete wall.

D. Backfill between existing shore and barrier concrete walls with compacted clay.

a. Existing wing walls shall remain. Top 1'-0"+/- of existing wing walls shall remain exposed (SHPO request)

E. See "REF_Conc for Menasha Fish Barrier" for marked-up reference drawings showing a similar barrier construction. Dimensions and elevations have been marked up for Menasha. Also see "REF_SR-Dimensions overview" for approximate concrete and backfill area dimensions.

a. Concrete work may require additional support and/or pumping/water drain-down during construction based on the existing soils.

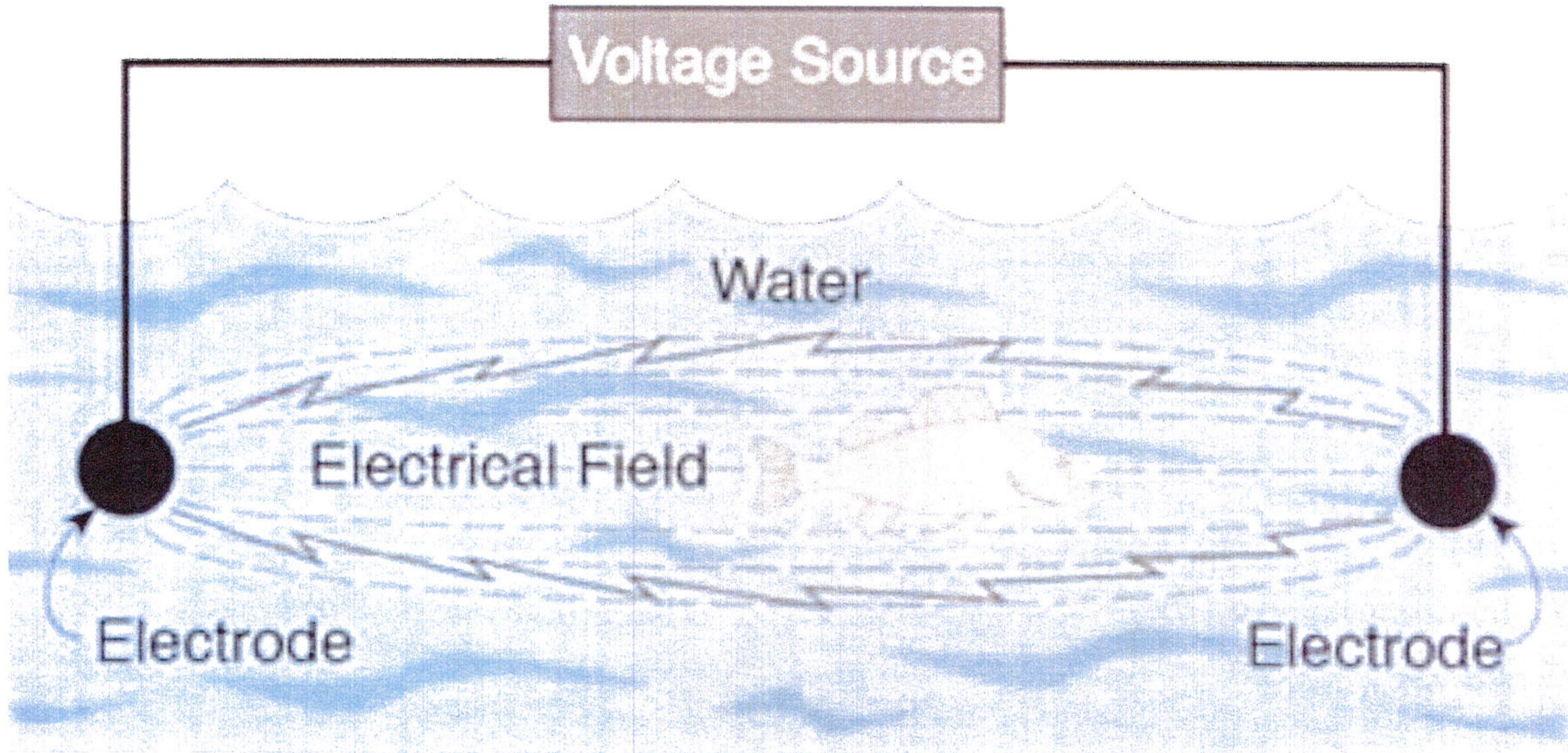
F. See "Exist Menasha Lock 33_bldg" for existing building construction. This building is not considered historic.

a. Construction will include:

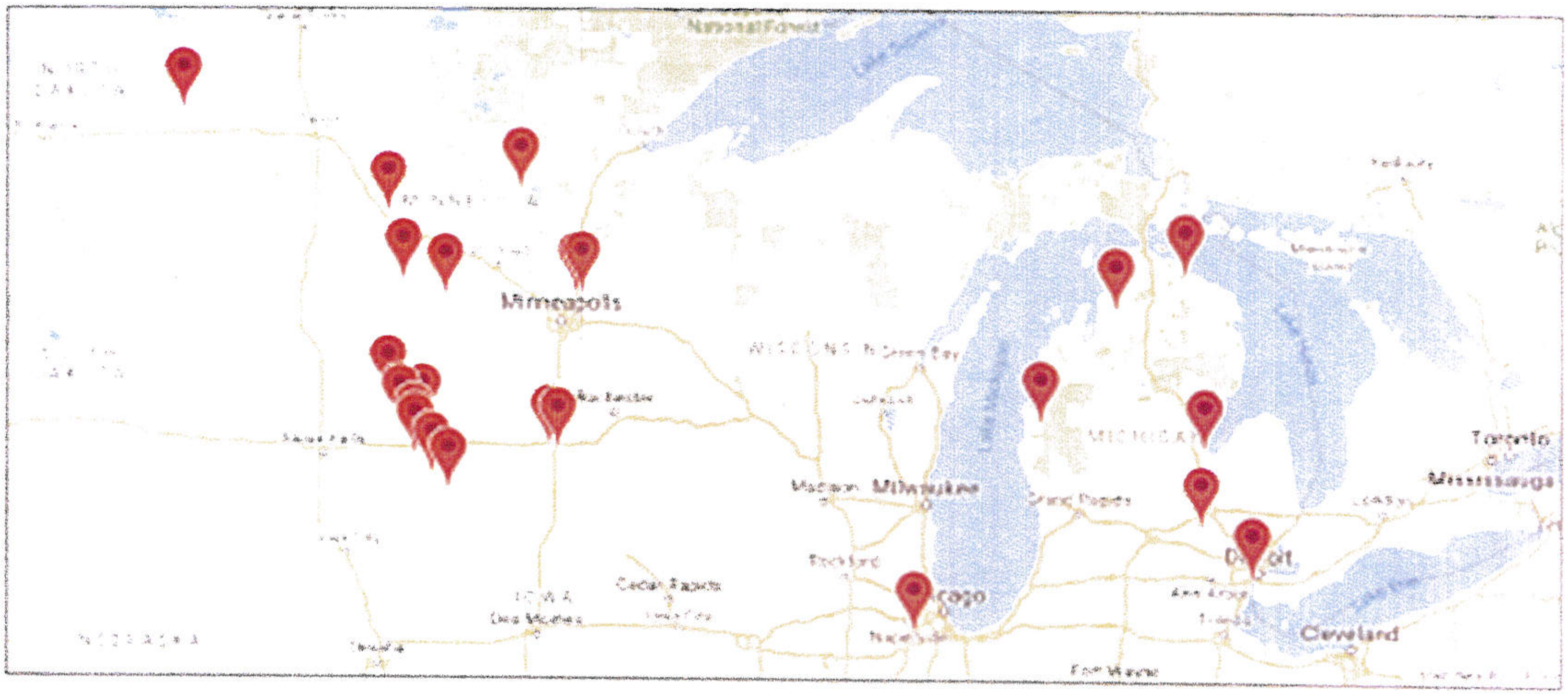
1. Demo of interior wall wood paneling
2. Insulate walls and roof, install new gyp board or plywood on interior of walls for equipment mounting.
3. Provide and install A/C unit.
4. Install new controls and power conduits thru walls.
5. General building repairs – this control building is in fair condition and should only require minimal work.
6. Install stop

G. Demo existing approx. 8' x 10' block toilet building. Abandon existing sewer line from toilet building to former/demo'd lock house. Tie new toilet building to street sanitary sewer and water.

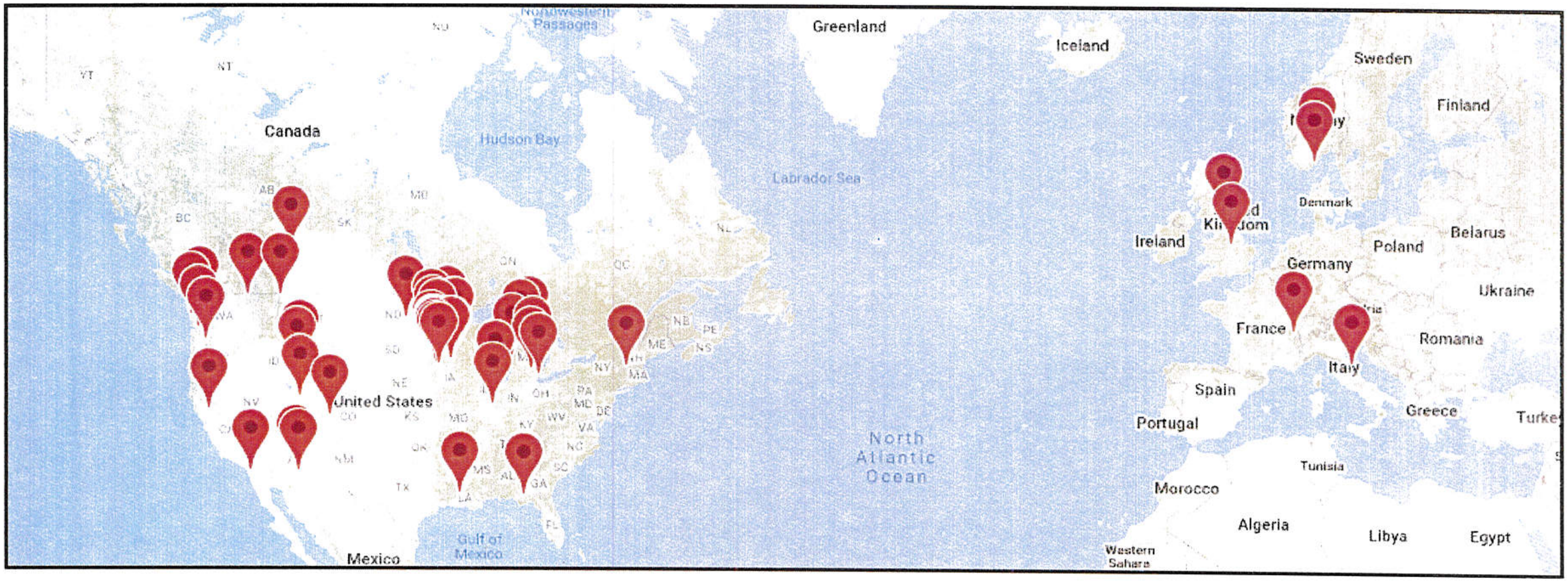
H. New toilet building to house (2) ADA rooms. Construction shall be 8" CMU walls with wood truss roof. Include enclosed room on north side of toilets to house generator, UPS, battery back-up. Run natural gas from street to fuel generator. See preliminary building sketch SK-1.


Voltage Source
Water
Electrical Field
Electrode
Electrode

Smith-Root Electric Barriers in the Upper Midwest



- 2 more currently under construction in Minnesota


Greenland
Iceland
Sweden
Finland
Canada
Hudson Bay
Labrador Sea
Denmark
Belarus
Ireland
Poland
Germany
Ukraine
France
Romania
Italy
Spain
United States
Portugal
Greece
North Atlantic Ocean
Tunisia
Morocco
Algeria
Libya
Egypt
Mexico
Gulf of Mexico
Western Sahara

Jeremy Cords

From: Phil Ramlet <Phil.Ramlet@omnni.com>
Sent: Tuesday, September 11, 2018 3:42 PM
To: Jeremy Cords; Jason Kent
Cc: Tim Bolwerk; Cari Bodoh
Subject: FW: FRNSA, Menasha Lock, Menasha Fish Barrier - estimate
Attachments: FRNSA Menasha Fish Barrier - Proposed Notes.pdf

Jeremy/Jason

In February 2018, we calculated a conceptual cost estimate based on the attached information. Construction costs have increased since then so perhaps increasing the estimate to $2.3-2.5 Million is appropriate.

Jason... your input would be appreciated.

Phil Ramlet
President/CEO
OMNNI Associates, Inc.
One Systems Drive
Appleton, Wisconsin 54914-1654
920.830.6112
http://www.OMNNI.com

From: Cari Bodoh
Sent: Tuesday, September 11, 2018 3:05 PM
To: Phil Ramlet <Phil.Ramlet@omnni.com>
Subject: FW: FRNSA Menasha Fish Barrier - estimate

From: Cari Bodoh
Sent: Wednesday, February 14, 2018 10:24 AM
To: Phil Ramlet <Phil.Ramlet@omnni.com>
Cc: Tim Bolwerk (Tim.Bolwerk@omnni.com) <Tim.Bolwerk@omnni.com>
Subject: FRNSA Menasha Fish Barrier - estimate

Estimated total project cost: $ 2,135,000.00 (this cost includes a 20% contingency on top of the breakdown below)

Approximate cost breakdown:

1. Pre-construction: $ 52,500.00
   a. Includes: archaeological, geotechnical, bathymetric survey downstream, ground survey, hydrologic analysis downstream and visual review of existing concrete.
2. Construction: $ 1,100,000.00
   a. Includes: installation of coffer dam, portage installation, pumps to flush fish from barrier, new toilet building with generator/transfer switch/storage batteries, refurbish existing building for controls, electrical installation, concrete work for barrier channel.
   b. Excludes: construction of any ADA access path or lifts. Yet to be determined if it is necessary for people to exit their boats.
3. Miscellaneous: $ 19,000.00
   a. Includes: allowance for signage, solar aerators at portage.
   b. Excludes: costs for reviews and permits (DNR, ACOE, EPA, US Fish & Wildlife, SHPO, Winnebago County)
4. Design: $ 74,000.00
   a. Includes: portage design, new building, building refurbishment, ADA access path and/or lift, site/civil.
5. Equipment (Smith-Root): $ 533,648.00
   a. See Smith-Root for breakdown of equipment and design inclusions/exclusions.

Thanks-

Cari Bodoh, PE
Structural Engineer

OMNNI ASSOCIATES

OMNNI ASSOCIATES, INC.
ONE SYSTEMS DRIVE, APPLETON, WI 54914
P:920-830-6130 | F:920-830-6100 | C:920-252-1805

A Review of Round Goby Swimming Capabilities, Behaviors, and Habitat Preferences to inform Colonization Deterrence Applications in Waterways

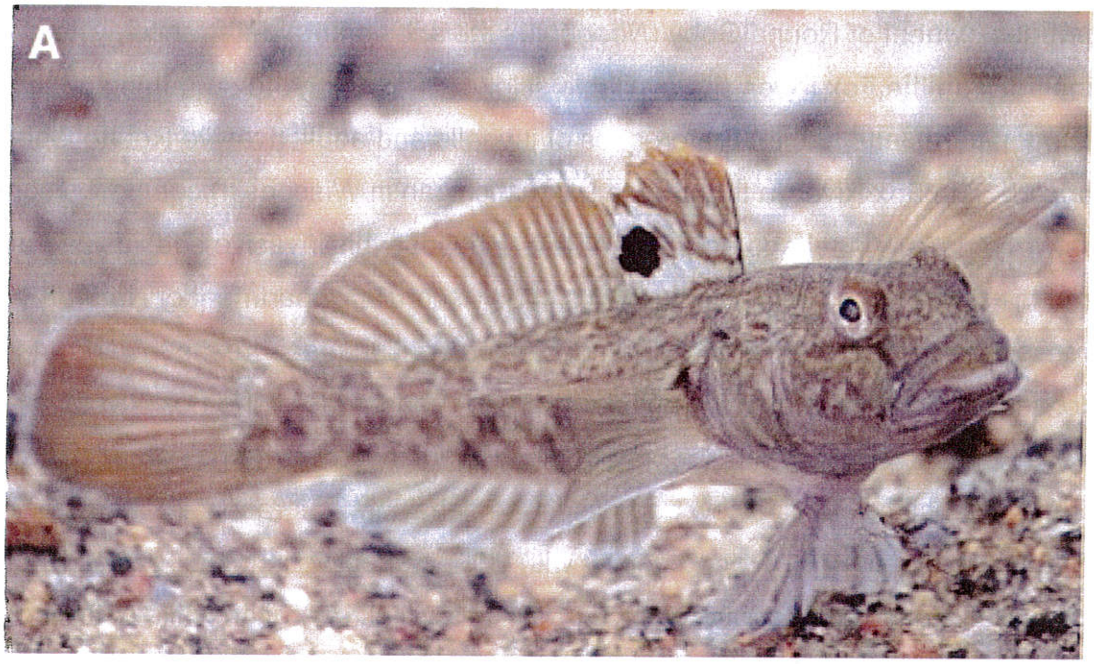


Figure 1. The Round Goby (Neogobius melanostomus) with characteristic black spot on first dorsal fin and its fused pelvic fin (from Figure 1A in Hirsch et al. 2016a).

Prepared by:

Carl Burger
Senior Scientist
Smith-Root, Inc.
Vancouver, WA

In Consultation with:

Nicholas Johnson, PhD
Research Ecologist
USGS Great Lakes Science Center
Hammond Bay Biological Station
Millersburg, MI

Executive Summary

To inform deployment of Round Goby (*Neogobius melanostomus*) deterrence systems at the Menasha Lock on the Fox River, the available science describing the swimming behavior, migrational patterns and habitat preferences of juvenile and adult invasive Round Goby was summarized. The Fox River (a tributary to Lake Michigan in Wisconsin) comprises some 17 locks between Lake Winnebago and Green Bay. Because this invasive species had already colonized the Great Lakes in the early 1990's, the Wisconsin Department of Natural Resources promulgated rules for invasive species prevention measures to thwart range extensions in Wisconsin waters. There is a desire to reopen one of the Fox River waterway structures (Menasha Lock) to regular boat traffic, without incurring the risk of further Round Goby range extensions. Our review addresses the behaviors, migrational patterns and life history habitat requirements of round gobies with this perspective in mind: exploit Round Goby life cycle weaknesses for strategies that can allow lock operation while deterring upstream movements and reducing this species' proclivity for range extensions.

The review was substantive. It examined global sources of information on Round Goby colonizations and their various life history requirements and adaptations. Objectives focus on an improved understanding of Round Goby swimming behaviors and habitats to guide decision-making for potential fish deterrence applications. Our aim in this literature review is to summarize existing knowledge on this species and review its potential for upstream movement at sites such as a proposed electric barrier at Menasha Lock. Thus, we consider the various life-stage adaptations and swimming behaviors of round gobies, their habitat preferences, and known environmental factors that either limit or foster range extensions. A better understanding of this species' biological and physical requirements can help elucidate life history vulnerabilities and/or aid in the development of deterrence strategies and technologies to reduce the risk of range extensions through the subject lock and environs.

Key Findings: Adults. Our review shows that in general, the Round Goby can live up to 5 years, attain maximum total lengths up to 25 cm, and achieve sexual maturity when 1+ to 3 years old. Maximum size differs in various localities, from 12 cm for males and 11 cm for females in the upper Detroit River, to 25 cm for males and 19 cm for females in Europe. A

main taxonomic anomaly is the presence of a fused pelvic fin on round gobies that forms a suction cup or disc for "burst-and-hold" behaviors that aid upstream movement in rivers.

Based on research results of Round Goby swimming behaviors from three published accounts, gobies are quite adept at using "burst-and-hold" or "burst-and coast" strategies to promote upstream movements in strong water velocities. The fused pelvic fin adaptation allows round gobies to "hold-station" in various flow regimes. Therefore, velocity barriers are unlikely to be an effective upstream migration deterrent in waterways.

Round gobies are able to maintain (indefinitely) swim speeds less than 35.5 cm/s but a proportion can maintain speeds >75 cm/s for "burst swims" up to a half-minute in duration (suggesting that with a "burst-and-hold" strategy, these fish could navigate flows, through successive attempts, at levels just less than their maximum-burst swimming capabilities. A swimming endurance model (Tierney et al. 2011) indicated that flow rates would need to be >125 cm/s to prevent upstream movement by round gobies in areas free of refuge recovery habitat. Other swimming speed research showed no significant difference in maximum swimming speed and station-holding endurance capabilities between lake and river-origin fish. Apparently, river fish are not better swimmers than round gobies from lake populations. Maximum speed and endurances were similar, indicating that the unidirectional, higher flows found in rivers are not strong enough to act as dispersal barriers for round gobies. However, we found published evidence (Savino et al. 2001) that an electric barrier successfully deterred round gobies from accessing a Lake Michigan tributary stream. Thus, an electric barrier (leveraged with any natural hindrance effects from water velocity) warrants consideration for the Menasha Lock deterrence application.

Diurnal Behavior: Adult gobies were more active on rocky substrates (as opposed to sandy habitats) during daylight hours than at night. These findings were statistically significant and concluded that the proclivity for daytime activity may lower the risk for predation.

Key Findings: Juveniles. In the Great Lakes region, round gobies spawn from May to October in a range of water temperatures from 9 to 26 °C. Males prepare and guard the nest from intruders through the incubation and hatching periods. Various physical locations are used for nest construction (each in some form of underwater structure forming a cavity with a single opening).

Data on Round Goby juvenile swimming speeds were quite scarce. However, we found references to an account published in a Russian journal. Initial swimming speeds of newly hatched, 5.5 mm fry were 2 cm/s and swimming speeds of 6 mm fry three days after hatching were 4.4 cm/s. Those unseen data come from a paper by Logachev and Mordvinov 1979, as cited by Marsden et al. 1996. We found no other accounts of larval swimming speeds.

Review findings also underscore the adaptive nature of this harmful and dangerous invader. Its adaptations include repeat spawning every 18-20 days, portion spawning, hidden nest construction, parental brood care, an unusual egg shape having strong substrate attachment capabilities, a very short embryonic development period coupled with relatively fast free-swimming independence, and utilization of varied habitats and water qualities. Canadian modeling studies reinforce such risks and concerns: Round Goby range expansions of 9.3 km/year were predicted in high-quality habitats.

Diurnal Behavior: Of high importance to the purposes of this review, we found evidence for a diel vertical migration pattern among newly hatched, 6.5 to 8.9-mm Round Goby fry. Based on ichyhyoplankton net tows in two separate studies, newly emerged goby fry were present in surface waters **only at night** (virtually none were found during daytime plankton tows). These data suggest a novel dispersal strategy for a species that lacks a swim bladder. The implication is that this negatively buoyant species may be employing a diel surface migration strategy for emergent fry to find and use surface currents for dispersal to new habitats. This unique behavioral adaptation may explain how round gobies found a way to North America in the ballast water of commercial shipping vessels. Relative to the Menasha Lock, the diel pattern does offer the potential to limit dispersal of juvenile Round Goby by enforcing a policy of not operating the lock at night. Also, the lack of any significant upstream current (i.e. flow into the lock from Little Lake Butte Des Morts), especially near the bottom of channel, severely limits the risk of upstream drift of larval gobies during daylight hours when the lock is in operation.

Key Findings: Habitat Preferences. The Round Goby is a bottom-dwelling fish that prefers rock/gravel substrates with interstitial spaces for both escape cover and for spawning in littoral areas of lakes and rivers. Gobies also seem to prefer human-made riprap, breakwaters, and rocky or coarse-gravel in inshore areas with abundant escape cover. Other preferred habitats include stony bottoms, mussel beds, areas near marina-type structures (piers, wharves, etc.) and on occasion, humus-containing bottoms overgrown with marine flora where they can reside with restricted movement.

In the Trent River near Lake Ontario, over 90% of the fish sampled were found in rock or gravel substrates (as opposed to sites composed of sand or macrophytic vegetation). Round Goby habitat preferences in three tributaries to Lake Erie, Pennsylvania were similar: rocky areas having moderate streamflow. But smooth, shallow bedrock areas in upstream portions of these streams were not used, presumably because they contained fewer ledges and crevices than found in deeper, more open stream areas. Shallow bedrock areas appear to act as a barrier to colonization and further upstream movement by round gobies.

Management Implications: Based on our review, the following management implications are offered:

(1) Water-velocity alone is unlikely to be an effective deterrent to halt the spread of adult Round Goby. However, an electric barrier was successful in blocking goby movement in a Great Lakes tributary. Furthermore, the effectiveness of Round Goby deterrence systems such as graduated-field electric barriers may be improved if built on smooth, bedrock-type characteristics void of goby refugia.

(2) Research reviewed on the vertical migrations and diel periodicity of newly emerged Round Goby fry provide additional implications for managers concerned about risks of goby transport at waterway structures. The science we reviewed (especially Hensler and Jude 2007) strongly suggests that larval gobies are only in the water column at night (i.e. in surface waters). Because the swimming abilities of these 6 to 9-mm larvae do not exceed 5 cm/s, and there is strong evidence that their dispersal strategy is to drift with water currents, there is little risk of their upstream movement in an area with no upstream current and occasional strong downstream current (when water is spilled from the lower lock gates). If the lock is operated only during daylight hours when larvae are absent from the water column, there should be no opportunities for upstream transport of larvae, suggesting that deterrence efforts need to instead focus on adult fish.

(3) The localized site fidelity of the Round Goby coupled with its preference for rocky, cobble substrates and underwater structures indicate that transport and colonization risks can be reduced or eliminated when these habitats are unavailable. Because smooth, bedrock-type areas were found to act as a barrier to Round Goby colonization and upstream range extension, the addition of such streambed modifications (replica structures) could serve to minimize goby presence downstream of waterway projects. However, such efforts may be costly and may present stream-bed engineering challenges. Other technologies (e.g. graduated-field, electric fish barriers) can provide better and cheaper solutions for Round Goby deterrence at Menasha Lock or other areas, as this type of electric barrier has achieved Round Goby deterrence success (Savino et al. 2001).

Introduction

A lock system on the Fox River, a tributary to Lake Michigan in Wisconsin, has had a varied history since the 1850's, with multiple operators including the U.S. Army Corps of Engineers. In 2001, the Wisconsin State Legislature created the Fox River Navigational System Authority (FRNSA) to take ownership of some 17 locks between Lake Winnebago and Green Bay. The Menasha Lock is the upstream-most of these locks, providing a boat connection between Lake Winnebago and the impounded part of the Fox River known as Little Lake Butte Des Morts. The Menasha Lock, shown in Figure 2, is typically open from mid-May to early October, and the average annual usage during this period is about 1,500 boats. The lock is only operated during daylight hours.

Figure 2. Menasha Lock from upstream (Lake Winnebago), looking north. Source: Smith-Root, Inc.

In 2009, the Wisconsin Department of Natural Resources promulgated new rules for invasive species that require preventative measures to thwart range extensions into Wisconsin waters. A key target of such legislation was a highly invasive fish species, the Round Goby

(*Neogobius melanostomus*), which had already colonized the Great Lakes. One of the Fox River waterway structures (Menasha Lock) is the focus for this review. Managers want to reopen Menasha Lock to regular boat traffic while simultaneously deterring movements of gobies, without incurring risks of further range extensions through the lock.

The Round Goby is an aggressive bottom-dwelling fish from the Ponto-Caspian region of southeast Eurasia (i.e. Black and Caspian seas) that extended its range to areas of the Baltic Sea (Skora and Stolarski 1993) and the Laurentian Great Lakes (Jude et al. 1992) during the summer of 1990. This invasive species now occurs in both brackish and fresh waters in numerous areas around the world, especially in major river systems and lakes in Europe and North America, where large populations have become established (Kornis et al. 2012; Bonislawska et al. 2014). Various life stages of the Round Goby were likely transported to the Baltic Sea's Gulf of Gdansk and to North America's Great Lakes in the ballast water of Ponto-Caspian shipping vessels in the late 1980's (Corkum et al. 2004). Successful fish invaders are tolerant of environmental change or can survive harsh conditions, as has this euryhaline species throughout the Great Lakes, despite strict ballast water exchange legislation (Ricciardi and MacIsaac 2000). Round Goby species colonized all five U.S. Great Lakes in just 5 years (Jude 1997).

A small, soft-bodied, bottom dwelling fish, the Round Goby can live up to 5 years, attain maximum total lengths up to 25 cm, and achieve sexual maturity when 2 to 3 years old (Bronnenhuber 2010). Maximum size differs in various localities, from 12 cm for males and 11 cm for females in the upper Detroit River (MacInnis and Corkum 2000), to 25 cm for males and 19 cm for females in the Gulf of Gdansk, Poland (Sapota 2012). Although similar in appearance to North American freshwater sculpins (*Cottus* spp.), a main taxonomic difference is the presence of two, distinct pelvic fins on fish in the family Cottidae versus the fused pelvic fin found on round gobies (see Figure 1).

Round Goby characteristics include frog-like eyes, a black spot on the dorsal fin and the fused pelvic fin that helps form a suction disc on the fish's ventral surface (Corkum et al. 2004; State of Michigan, no date). This species is often found on hard substrates in association with another Eurasian invader, the Zebra Mussel (*Dreissena polymorpha*), a major component of goby diets owing to their pharyngeal teeth that can crush mollusk shells as soon as juvenile gobies grow to a length of about 6 cm (French and Jude 2001). Zebra mussels may have facilitated Round Goby invasions by providing an abundant food source (Ricciardi and MacIsaac 2000).

The spread of an invasive species such as the Round Goby is a serious challenge for natural resource managers because once established, containment is difficult, native fish species become threatened, and major shifts in aquatic species' population and ecosystem structure are inevitable. Several studies have shown the harmful effects of Round Goby predation on the eggs of native fish fauna (Sapota and Skora 2005; Kornis et al. 2012) and an ability to outcompete indigenous species for food, shelter and spawning habitat (Lauer et al. 2004; Balshine et al. 2005).

A very recent publication compared the early and the late phases of the European invasion at the population level in the Danube River between Austria and Germany (Brandner et al. 2018). These authors noted an upstream invasion by the Round Goby of some 30 river km in the Danube within just 4 years. More importantly, this research keyed on the principles of adaptation and genetic plasticity as prime factors in goby colonization success rates. Large-sized pioneering invaders (the earliest colonizers), with greater exploratory behavior, highly adaptive phenotypic plasticity, and increased competitive ability pave the way for colonization success (Brandner et al. 2018).

Such adaptive capabilities and genetic plasticity observations among various Round Goby invasions are strongly supported by other recent research. Kornis et al. (2017) examined the attributes and life history patterns of round gobies that had colonized Lake Michigan versus those living in the lake's adjacent tributaries (stream habitats). Tributary gobies grew much faster, had shorter life spans, and achieved sexual maturity at younger ages compared to those residing in Lake Michigan proper. This Lake Michigan research suggests an additional concern: that divergent life history patterns emerge as a result of local adaptations following initial Round Goby invasions. Adaptive divergences can potentially act as springboards for range extensions by invasive species (Kornis et al. 2017). The observed differences and suggested divergences noted by these authors between lake and tributary round gobies are consistent with life-history theory predicting rapid growth, early reproductive maturity, and a greater investment in reproductive strategies during population establishment in new, low-density habitats (Bøhn et al. 2004). However, and when body sizes were compared among round gobies in an initial colonization location (68 to 77 mm) with those (74 to 92 mm) in newly colonized areas in the Trent River, Ontario, the smaller fish sizes in the initial colonization habitat were thought to be a result of density-dependent factors (Gutowsky and Fox 2011). Round Goby densities reported in some Lake Michigan habitats approach 130 fish/m^2 (Chotkowski and Marsden 1999).

The state of knowledge of these impacts, adaptations and behavioral abilities among invasive Round Goby populations is therefore crucial to our understanding of potential life-cycle vulnerability points; knowledge that can help allocate resources, motivate containment strategies, and implement technologies to deter or arrest range extensions.

The goal of this paper is to focus and present findings on Round Goby life-cycle and behavior-related adaptations from an intensive, global literature review having three objectives:

(1) Describe swimming performance and diurnal behavior of adult round gobies to inform management prospects for potential barrier designs;

(2) Provide a similar review of Round Goby juvenile swimming and diurnal behaviors; and

(3) Describe the types of lacustrine and riverine habitats preferred by juvenile and adult gobies (including their spawning and rearing habitats) to inform which habitats are high-risk for Round Goby transport and colonization..

Methods

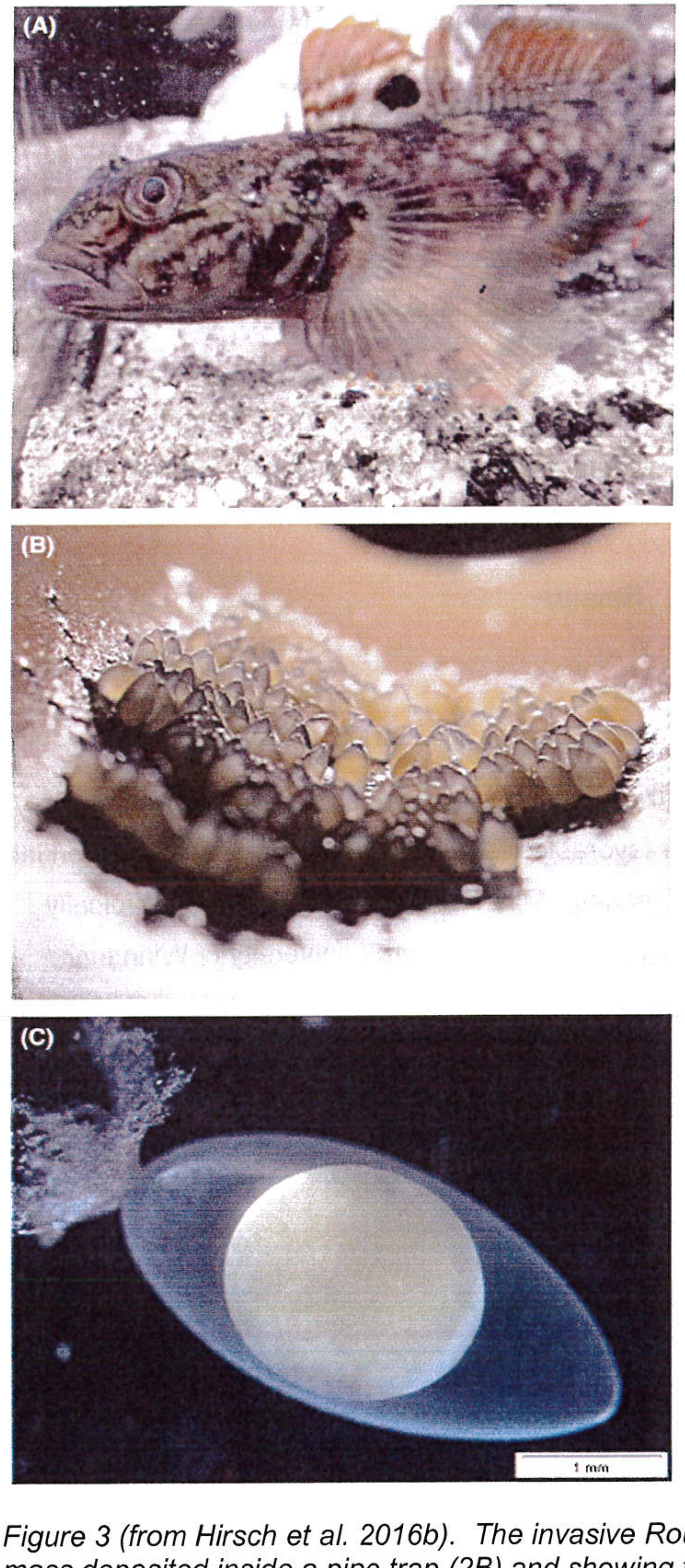
Our review was structured to present information on (1) adult Round Goby swimming capabilities and any reported diurnal behaviors or patterns, (2) larval and juvenile swimming behaviors and migration patterns, and (3) the habitat preferences of all life stages. These goals were established in attempts to garner data and information useful to natural resource and engineering managers who approve and/or operate waterway projects where the risk of further Round Goby range extensions is deemed to be high. What types of habitats do round gobies prefer? What types of water velocities can they navigate and overcome? Are there any life history weaknesses that can be exploited to minimize the risk of opening new colonization transport avenues? And are there any diurnal patterns in goby behavior whose knowledge can be used to lower those risks?

We used online commercial databases, literature search tools and colleague contacts to collect and assess information relevant to our objectives. Key search words and phrases were used with prioritization on papers and publications involving Round Goby life history requirements, population dynamics and the unique life history adaptations that have made this species so successful in new environments. However, we focus our review on those results most applicable to the potential reopening and operation of the Menasha Lock on the Lower Fox River in Wisconsin, where deterrence strategies and barriers are now under consideration.

Results

Morphology and Life History Background:

The Round Goby is a prolific, repeat spawner over an extended reproductive season. Research by Jude et al. (1992) suggests that round gobies have the ability to spawn every 18-20 days up to six times per year under favorable reproductive conditions. Thus, potentials exist for production of large numbers of offspring. Males guard the eggs that are typically deposited in nests within a protective cavity. Dr. Lynda Corkum (University of Windsor, Canada) provides a useful summary of Round Goby identification and reproductive traits with a video of Round Goby spawning behavior on her website link: http://web2.uwindsor.ca/courses/biology/corkum/goby/goby.htm



A host of papers provide information on Round Goby size, from pre-hatch egg diameter to adult length and fecundity at reproductive maturity. Several examples are highlighted to provide the reader with perspective on approximate sizes at different life history stages.

Figure 3C (from Hirsch et al. 2016b) depicts the unique shape of Round Goby eggs (described in more detail below) and an adult egg mass (2B).

Hirsch et al. 2016b also studied the resiliency of Round Goby eggs. They found a resistance to physical removal (a 90 mN attachment strength of individual eggs) even if exposed to a rapid water flow of 2.8 m/s for 1 h (and a >95% hatching success after eggs were out of water for 24 h). N (in newtons) is a stress-force value of tensile strength. Round Goby eggs seem to have attachment strengths akin to the byssus threads used by marine mussels for attachment to wave-washed, rocky coastlines (Bell and Gosline 1995).

Figure 3 (from Hirsch et al. 2016b). The invasive Round Goby and its adhesive egg mass deposited inside a pipe trap (2B) and showing the adhesive attachment filaments on a single, ellipsoid egg (2C).

In a Round Goby study at a university in Poland, Bonislawska et al. 2014 collected sexually mature fish from an area in the Baltic Sea known as Puck Bay. Males (average length about 15 cm) and females (average length 12.4 cm) were transported to tanks having sand and stone bottoms with water quality conditions (e.g. dissolved oxygen, temperature and salinity) similar to those in capture locations.

The fish collected by Bonislawska et al. spawned naturally in confinement, with newly laid eggs (uncharacteristically ellipsoid or "pear-shaped" in nature) attached to tank substrates. Egg height approximated 2.7 mm and egg width ranged from 1.3 to 1.9 mm. Resulting fry began active feeding 5 days after hatching (average larval length 10.3 mm), when yolk sacs were reabsorbed. After 90 days, mean length was 24.8 mm and mean weight was 0.18 g.

In the Great Lakes region, round gobies spawn from May to October but require a range of water temperatures from 9 to 26 $^{\circ}$C for spawning success (MacInnis and Corkum 2000). Unlike reports from Europe and the findings of Bronnenhuber 2010 (that female Round Goby mature at age 2), MacInnis and Corkum found sexually mature, female round gobies at just 1 year of age in the upper Detroit River. Whereas fecundity appears to be much higher in European round gobies (Bonislawska 2014), MacInnis and Corkhum noted mean fecundities of only 198 eggs per nest, with nests in the upper Detroit River being used more often by more spawning females than in European goby nests. Phillips et al. 2003 also found female round gobies maturing at 1+ years of age in Pennsylvania tributaries to Lake Erie, with fecundities ranging from 86 to 591 eggs. Apparently, males migrate from deeper water to establish spawning areas (dig out nests) in shallow water before females arrive at spawning locations (MacInnis and Corkum 2000).

Round Goby reproduction involves five stages: territory establishment, nest preparation, courtship behavior, spawning, and parental care of the eggs. Male gobies construct the nest (Marsden et al. 1996). European data suggest that males die after spawning (when nest guarding activities are complete), but females can reproduce in subsequent years and more than one female can spawn in a given nest (Sapota 2012). Also, the reported life span of the Round Goby is somewhat short: 3 to 4 years in the Gulf of Gdansk (Sapota 2012) and up to 5 years in the Great Lakes region (Bronnenhuber 2010).

Various physical locations are used for nest construction (each in some form of cavity with a single opening). Using cement gland excretions, nest substrates are coated by the male whereupon females "glue" each egg to the nest cavity's roof (Marsden et al. 1996). These authors report that nests are generally built under stones, logs or other protective cover where males guard and fan the eggs to promote aeration and reduce fungus. Marsden et al. 1996 cite additional reproduction-related information (unseen) in difficult-to-obtain Russian papers (Logachev and Mordvinov 1979; Moiseyeva 1983; Moskal'kova 1989):

- Round Goby eggs are 3.4 to 3.8 mm in diameter and develop in 14 to 15 days at 19-21 °C or 18 to 20 days at 17.5-19 °C under laboratory conditions.
- Round gobies lack a true larval stage (most researchers instead refer to "fry").
- Fry emerge from eggs at 5.5 to 5.7 mm in length, begin feeding on prey (such as juvenile brine shrimp) within a couple of days of hatching, and are 6 mm in length by day three.
- Newly hatched fry are capable of swimming speeds averaging 2 cm/s. After 3 days, they can swim at speeds of 4.4 cm/s. These data come from Logachev and Mordvinov 1979, as cited by Marsden et al. 1996.

Other difficult-to-obtain publications in Russian (Berg et al. 1949 and Nikolsky 1954, as reviewed and cited in Bonislawska et al. 2014) provide further data on reproductive behaviors. Those Bonislawska-cited sources mention spawning times from April until August for round gobies in Black and Caspian Sea-related habitats. Egg fecundities ranged from 300 to about 6,000 eggs laid in masses in portions (i.e. multiple egg deposits) at water depths from 0.5 to 6 m at 15 to 16 °C. Hatching occurred within 4 to 7 days as water temperatures rose (but larvae remained attached for several more days to the adult male-guarded nest via their ventral suction discs). Different thermal regimes and water quality conditions undoubtedly contribute to reproductive timing and physical size differences among the varied habitats used by the Round Goby. In research conducted by Kornis et al. 2017, gobies residing in Lake Michigan tributaries grew much faster (122.3 mm at age 2+) versus 65.7 mm for lake-residing gobies at the same age (with tributary fish attaining reproductive maturity in just 1.6 years versus 2.4 years for lake-residing fish). Kornis et al. 2017 suspect that the warmer water temperature profile in their tributary study streams (versus a colder thermal regime in Lake Michigan) was a key driver of the divergent life histories they discovered. But some very important points and management implications can be drawn from studies like the Kornis et al. work:

- Life history divergence is likely when introduced species spread into suboptimal, novel habitats. The more a species spreads, the greater its adaptive requirements.
- This propensity (for local adaptations) also requires a high degree of phenotypic plasticity. Gradual genetic changes (via natural selection) are undoubtedly a reason for what may otherwise appear to be conflicting life history data from various authors evaluating different study sites.
- Also, divergent life histories may be prevalent among invasive species that are now engaged in secondary invasions into connected habitats.

Our review found what is purportedly an incidence of intersex (simultaneous occurrence of both male and female gonadal tissue) among round gobies in Europe (two harbors in Poland). Gonad analysis of two male fish from separate harbors displayed the presence of female gametes in histological examination of testes. However, and as pointed out by the authors (Guellard et al. 2015), these anomalies could be the result of the improper discard of estrogenic endocrine disruptors in harbor waters (compounds known to induce sex-changing influences in other fish species). In fact, Marentette et al. (2010) found similar evidence among male round gobies from Hamilton Harbour, Canada. However, additional concerns (that round gobies have a propensity to concentrate pollutants in their tissues and thus promote ecosystem food-web contamination in apex predators) may be the greater risk.

In Lake Erie, Smallmouth Bass (*Micropterus dolomieu*) males vigorously defend (guard) their nests from the Round Goby's propensity to prey on eggs of other species. This heightened activity among bass can cause significant declines in their weight and energy (Steinhart et al. 2004). Therefore, increased parental care costs (owing to the presence of round gobies) can affect future growth, reproduction, and survival when Smallmouth Bass approach critically low energy reserves.

From an overall perspective, newly colonized round gobies in the brackish waters and lakes of North America are smaller, mature earlier, have a male biased operational sex ratio and are more short-lived compared with round gobies from Ponto-Caspian native habitats (Corkum et al. 2004).

Our review findings underscore the adaptive nature of this harmful and dangerous invader. Its adaptations include repeat spawning every 18-20 days, portion spawning, hidden nest construction, parental brood care, an unusual egg shape having fast substrate attachment capabilities, a very short embryonic development period coupled with relatively fast, free-swimming independence, and utilization of varied habitats and water qualities. Canadian modeling studies by Brownscombe et al. 2012 reinforce such risks and concerns: their research model predicts a range expansion of 9.3 km/year in high-quality habitats in the Trent-Severn Waterway in Ontario, with a 5% probability that highly mobile round gobies could disperse up to 27 km/year.

Objective 1: Round Goby Swimming Speeds and Patterns (Adults)

In comparison with the numerous papers and publications on occurrence, colonization and life history information, comparatively fewer research studies and reports have been undertaken to assess and quantify the swimming speeds and patterns of round gobies. Two of the best, however, are studies published by Tierney et al. 2011 and Gilbert et al. 2016, using stepped velocity tests where fishes are brought to fatigue through incremental increases in water flow and the speed at fatigue is considered the critical swimming performance (described as U_{crit}; see Gilbert et al. 2016). The U_{crit} test (Brett 1964) was pioneered for research on salmonid swimming performance. In fishes that employ alternate strategies to advance or maintain positions in flowing water, the point of fatigue will relate to water flow speed, but will result from a combination of energy exerted in substrate holding *and* swimming (Gilbert et al. 2016). Fortunately, we are not dealing with various species of Hawaiian gobies (they also use a fused pelvic fin as a suction disc). Hawaiian gobies can gradually "climb" 350-m high waterfalls to reach upstream spawning grounds (Blob et al. 2007)! The fused pelvic fin is a unique adaptation among gobiid fishes that plays a very important role in Round Goby migration and dispersal (Jude et al. 1992).

The Gilbert et al. 2016 Swimming Speed Study:

In swimming performance tests of 23 adult gobies from the upper Detroit River (mean mass 16.9 g and mean total length 11.2 cm), Gilbert et al. 2016 used a modified respirometer comprised of a 1-m square tube with internal dimensions of 10 x 10 cm as their test apparatus. A rear gate made of stainless steel was electrified with low voltage (<5 V) to prevent gobies from resting at the rear of the flume. Fasted adult gobies (no juveniles used) were selected for testing and acclimated to the minimum flow in the test chamber (17.9 cm/s). Fish were brought through stepped increases in flow until they were unable to remain off the electrified rear grid for 5 s. Each step "height" was 7.5 cm/s and each step length was 10 min. Swimming behaviors (holding, "sliding," or swimming) were video-recorded and visually scored. Substrate holding was a primary behavior noticed in this research. The critical substrate holding velocity (U_{hold}) was the last flow speed at which holding accounted for >50% of total goby activity.

In the Gilbert et al. study, the U_{crit} critical swimming performance value (the water speed in which a position can be maintained for a prolonged time period) was measured at 34.8 cm/s. The last flow speed at which round gobies were able to hold the substrate for a majority of the time (U_{hold}) was 28.6 cm/s, with swimming as the primary behavior once fish were unable to hold the substrate. Results suggested that substrate holding ability was largely responsible for test fish to reach U_{crit} but with substantial, individual variation (e.g. some fish reached U_{crit} by using a "burst-and-coast" gait with greater than three bursts per min). In coarse, natural, stream substrates, round gobies may perform better because resting refugia could be used to replenish energy reserves during arduous, upstream dispersal forays.

The Tierney et al. 2011 Swimming Speed Study:

Round Goby swimming behavior was also evaluated by Tierney et al. 2011, who recorded activity in a 2-m flume using "critical swimming" (U_{crit}) and burst tests in both still and flowing water. Similar to the Gilbert et al. work, study fish also came from the Detroit River near Windsor, Ontario and were captured by hook and line and subsequently held for recovery at the University of Windsor for 6 months or more. The authors evaluated 24 female and 23 male fish having an average mass of 15 g and a mean total length of 11 cm. Goby swimming ability was measured and video-recorded in three ways: (1) by chasing (startling) fish in static water to ascertain maximum burst speed, (2) allowing volitional choice by fish to swim upstream or downstream, and (3) by motivating fish to swim in flowing water in a swim tunnel. Minimum flows in the flowing water tunnel trials were set at 17.9 cm/s and incrementally raised to 2x the maximum achieved by each goby tested. Like the Gilbert et al. study, a rear removable gate in the swim tunnel was electrified with low voltage (5 V) to prevent test fish from resting at the rear of the flume. Salient findings from Tierney et al. are as follows:

- Fish chased in still water exhibited average burst swimming speeds of about 1 m/s (97 cm/s) for either sex, corresponding to 9.3 body lengths (BL) per second, with individual speeds ranging from 15 to 162 cm/s (1.7 to 16 BL/s).

- Tests in still water further showed that round gobies (regardless of sex) became fatigued and unresponsive to stimuli in just over 2 min, with successive series of bursts at lower speeds. However, males exhibited 2x the number of bursts seen in female fish and males covered twice the total distance (about 12.2 m) traveled by females (5.7 m) in burst tests (about 110 versus 63 BLs).

- Volitional movement trials showed that gobies chose to move in the test flume under low-flow conditions after a period of some 4 hr. No sex-based movement differences were observed but fish covered considerable ground in the test environment (about 81.3 m, or 722 BL).

- Flowing water trials used the well-known "critical swimming performance" (U_{crit}) test to evaluate Round Goby behavior when forced to swim in a swim tunnel. In these trials, gobies used either a "burst-and-hold" or a "burst-and coast" strategy to deal with velocity. These trials soon became "critical station holding" abilities because all gobies retarded rearward movement by contacting the tunnel's substrate. Burst-and-hold distances averaged 35.5 cm/s (3.2 BL/s) whereas burst-and-coast distances averaged 65.8 cm/s (5.8 BL/s). In either case, behaviors were unrelated to fish sex.

- The majority of test fish spent greater time upstream than in downstream locations but the difference was not statistically significant. Researchers found no significant overall diurnal difference in the number of upstream versus downstream trips made by gobies (day: 36.4; night: 41.4). However, gobies made significantly more short trips at night (in an upstream direction) and were less active during the day (i.e. they exhibited a nocturnal bias).

- Maximum swim speeds of round gobies were unrelated to those that fish could perform when forced (with travel distances similarly unrelated to those observed when fish were forced). Results indicate that **gobies are able to sustain speeds of up to about 38 cm/s (3.4 BL/s) for indeterminate periods but that a marked and steady decrease in swimming duration occurs at swim speeds above 40 cm/s (about 3.6 BL/s).**

The research from Tierney et al. 2011 suggests that round gobies can choose to be very active swimmers, with daylight having only a marginal influence. When coerced, gobies can be formidable swimmers with somewhat powerful burst swimming capabilities and an ability to "hold-station" in fairly strong currents. Round gobies appear to be able to maintain (indefinitely) swim speeds less than 35.5 cm/s. About 18% of the gobies tested by Tierney et al. maintained speeds >75 cm/s for "burst swims" up to a half-minute in duration (suggesting that with a "burst-and-hold" strategy, these fish could navigate flows, through successive attempts, at flows just less than their maximum-burst swimming capabilities). **The authors provide a swimming endurance model indicating that flow rates would need to be >125 cm/s to prevent upstream movement by round gobies in areas that are free of refuge recovery habitat.**

The Hoover et al. 2003 Swimming Speed Study:

An additional paper on goby swimming speeds was reviewed. This comprised some earlier work by Hoover et al. 2003. These authors also examined critical swimming and holding behaviors during water velocity tests to quantify the maximum sustained swimming speed of the Round Goby in a somewhat smaller flume than used by Tierney et al. 2011. Hoover et al. tested 63 males and 34 females (total lengths ranged from 7.2 to 15.4 cm for males and 7.5 to 13.6 cm for females). They reported mean station holding speeds of 20.7, 42.4, and 52.5 cm/s on Plexiglas, sand, and gravel substrates respectively. In all experiments, round gobies spent very little time (<20%) swimming in the water column and preferred to stay on or in close proximity to the bottom substrates that were evaluated.

The Hoover et al. research subjected round gobies to a variety of flow rates from 15 to 75 cm/s, recording time to fish fatigue. Their research noted burst, prolonged, and sustained station holding at speeds from 15 to 20, 20 to 50, and 55 to 75 cm/s, respectively. At 17 °C, small gobies exhibited sustained station holding at 15 cm/s, prolonged station holding (from 0.5 to 44 min) at 20 to 50 cm/s, and burst station holding at 55 to 75 cm/s. Large gobies exhibited sustained swimming at 20 cm/s, prolonged swimming (0.5 to 72 min) at 20 to 50 cm/s, and burst station holding at 55 to 75 cm/s (larger fish having greater endurance than smaller cohorts). At 20 °C, small gobies exhibited prolonged station holding (0.5 to 61 min) at 15 to 55 cm/s, with burst station holding behavior at 60 cm/s.

However, and as noted above, 18% of the gobies tested by Tierney et al. 2011 maintained speeds >*75 cm/s* for burst periods as long as a half minute. And in still water, the Tierney et al. data show that 87% of fish maintained a speed >75 cm/s for at least 0.5 s. For Round Goby management and deterrence purposes, the Tierney et al. 2011 data seem to call into question those reported by Hoover et al. 2003 who suggested that flow speeds >75 cm/s would be a sufficient hydraulic barrier for Round Goby containment.

Other Data on Round Goby Swimming Speeds:

MS thesis research by Bronnenhuber 2010 also looked at maximum swimming speeds and station holding endurance for round gobies collected from both lake and river populations (encompassing habitats in or adjacent to Erie, Huron and Ontario Great Lakes). The author described methodology issues with her data and her interpretations for absolute U_{crit} and U_{hold} values (in obtaining data showing swim speeds that were over 100 cm/s and thus double or triple those reported by other researchers). Thus, these data may be questionable. But since the same methodology was used between all sample sites, one result should hold. **Bronnenhuber found no significant differences in maximum swimming speed and station holding endurance capabilities between lake and river fish.** Apparently, river fish were not better swimmers than round gobies from lake populations, as originally hypothesized. Maximum speed and endurances were similar, indicating that the unidirectional, higher flows found in rivers are not strong enough to act as dispersal barriers for round gobies (Bronnenhuber 2010).

Adult Diurnal Behavior:

In regard to potential diurnal behavioral patterns among adult round gobies, Ray and Corkum 2001 found adult fish to be most active on rocky substrates (as opposed to sandy habitats) during daylight hours than at night. Their findings were statistically significant and highly so. The authors concluded that the proclivity for daytime activity was geared towards lowering the risk for predation on adult round gobies. Belanger and Corkum 2003 attached tethers (25-cm monofilament lines) under the dorsal fin of round gobies (mean weight 8.5 g; mean total length 8.6 cm) to evaluate predation in sandy habitats with and without shelters. Results showed that 17 of 120 round gobies were missing from the sand habitats having no shelters whereas only 7 of 120 gobies went missing from the sand habitats *with* shelters. Such findings support the need for refugia and shelters (e.g. rocky cobble, crevices, shipwrecks, etc.) by round gobies to reduce their predation risk in newly colonized habitats.

Management Implications:

The subject of Round Goby swimming capabilities necessitates consideration of at least two key points regarding the findings for adult fish:

(1) The unusual, fused pelvic fin on round gobies (that distinguishes this fish from most other non-gobiid species) can be used as an effective suction disc in high, turbulent flows or while ascending inland rivers (Marsden et al. 1996; Bronnenhuber 2010) and even high waterfalls by some Hawaiian gobiids (Blob et al. 2007). This morphological adaptation allows for the successful "burst-and-hold" behaviors observed by Hoover et al. 2003, Tierney et al. 2011 and others (making water velocity barriers all the more challenging).

(2) Clean smooth substrates can minimize opportunities for adults to rest and recover when attempting to use "burst-and-hold" strategies to ascend upstream areas in rivers. For goby containment and/or deterrence applications, resource managers should consider all options to eliminate coarse cobble and rocky substrates in waterway projects where goby transport and colonization risk must be eliminated or reduced. **Rocky cobble substrates and underwater structures are preferred habitats for invasive round gobies because they offer refugia that promote rest-and-burst or rest-and-coast behaviors.**

Water-velocity barriers are unlikely to halt the spread of this invasive species. However, and if applications such as graduated-field electric barriers are being considered for goby deterrence, it may be possible to include some of the smooth, bedrock-type characteristics explained by Phillips et al. 2003 (see below) to reduce the risk of upstream transport and further range extensions if preferred rocky habitats cannot be removed or altered downstream of a waterway project site. A graduated-field electric barrier successfully blocked downstream Round Goby migrations in a Michigan stream (Savino et al. 2001). Whereas control fish moved repeatedly across a non-electrified barrier within 20 min time periods, movements were blocked when electric gradients up to 4.9 V/cm were applied (and only a single, dead goby was found below the barrier). Electric barriers have been highly successful at deterring various fish movements in many applications (Burger et al. 2015).

Objective 2: Round Goby Post-Hatch Behavior and Movements (Fry)

The offspring of round gobies typify a pattern of ontogeny and development common among livebearers and nest guarders: direct development. That is, the young emerge functionally and morphologically similar to adults and thus, lack a true larval stage (Marsden et al. 1996). For this reason, and as mentioned previously, newly emerged round gobies greater than about 6 mm in length (attained within a few days after hatching) are referred to as fry.

The embryonic development of the Round Goby is described by Bonislawska et al. 2014 (egg size and morphology information was previously presented, above). Newly hatched fry are about 5 mm in length. Yolk sac reabsorption is fairly rapid and occurs within 5 to 7 days, when the fry commence feeding on zooplankton (larger sizes of zooplankters are consumed through day 30).

Initial swimming speeds of newly hatched, 5.5 mm fry (2 cm/s) were reported above, as were the swimming speeds of 6-mm fry 3 days after hatching (4.4 cm/s). Those unseen data come from Logachev and Mordvinov 1979 (as cited in Marsden et al. 1996). Additional published data on the behavior and movements of Round Goby juveniles were limited

Diel Periodicity and Vertical Migrations of Newly Hatched Fry:

Earlier in our review, round gobies seem to be active during daylight hours when they avoid sand-laden substrates (Ray and Corkum 2001). A study by Hensler and Jude 2007 found quite the opposite when they sampled Round Goby fry in the Muskegon Harbor channel leading to Lake Michigan and at subsequent sites in Lake Michigan and Lake Erie. Collections relied on ichthyoplankton net tows at all sites from June through August, where catches resulted in Round Goby fry that were 7 to 8 mm in length (98% of fish sampled).

The most interesting part of the Hensler and Jude report is that Round Goby fry were most prevalent during nighttime collections at the water surface (with virtually no goby fry found during daytime tows and none longer than 8.9 mm in the surface nighttime collections).

These results constitute a very significant diel difference between nighttime and daylight plankton tow collections. The authors note that surface sampling sites were located some 2 km from known spawning habitat. **Hensler and Jude thus hypothesize that this finding (fry collections in surface areas remote from spawning habitat and only at night) is evidence for a diel vertical migration pattern** — which may be a Round Goby dispersal strategy for a species that lacks a swim bladder. The implication is that this negatively buoyant species may be employing a diel surface migration strategy for optimally sized fry (those 6.5 to 8.9 mm in length) to find and use surface currents for dispersal to new habitats. This unique behavioral adaptation may explain how round gobies found a way to North America (i.e. in nighttime ballast water extractions in estuaries by ocean-going vessels).

Results from Hensler and Jude 2007 are a somewhat surprising find, but not necessarily unique among gobiid fishes. Schultz et al. 2003 found a similar behavioral pattern for a cousin to the Round Goby, the Naked Goby (*Gobiosoma bosc*) in the Hudson River estuary, New York. Using plankton trawls, Schultz et al. also caught goby fry (having a mean length of 5.8 mm) in nearshore surface areas at night, particularly during neap tides. Their conclusion for this diel periodicity result was the promotion of transport for Naked Goby fry.

Management Implications:

The research we reviewed on vertical migrations and diel periodicity of newly emerged Round Goby fry has potential implications for managers concerned about goby transport risks at waterway structures. The science provided by Hensler and Jude 2007 (with support from Schultz et al. 2003 for a related gobiid fish) strongly suggests that larval gobies are only in the water column at night and utilize a nocturnal dispersal strategy where surface water currents and wind promote range expansion, similar to the strategies used by some marine species. Upstream water flows are not likely at Menasha Lock and lock openings for boat transport would occur only during daytime. Coupled with known larval swimming capabilities (<5 cm/s) and assuming that discharges from the lock when it is operated will typically exceed 5 cm/s, it is unlikely that Round Goby fry could ever navigate upstream during lock openings. If lock openings occur only during daytime hours, the risk of any upstream larval transport is thus precluded, and management should instead direct its focus on the deterrence of upstream-moving, adult round gobies (a very achievable goal based on the electric barrier results obtained by Savino et al. 2001).

<u>Objective 3</u>: River and Lacustrine Habitats Favored by the Round Goby

The Round Goby is a bottom-dwelling fish that prefers rock/gravel substrates with interstitial spaces for both escape cover and for spawning in littoral areas of lakes and rivers (Hirsch 1998). Gobies also prefer human-made riprap, breakwaters, and rocky or coarse-gravel inshore areas with abundant escape cover. In the Gulf of Gdansk, preferred habitats of round gobies include sandy, stony bottoms, mussel beds, areas near marina-type structures (piers, wharves, etc.) and even muddy, humus-containing bottoms overgrown with marine flora where they reside with restricted movements (Sapota 2012). In the Trent River near Lake Ontario, Gutowsky and Fox 2011 sampled 607 round gobies from upstream and downstream colonization sites. The predominant habitats selected by round gobies constituted rock and gravel (over 90% of fish found in these habitats) as opposed to sites principally composed of sand or macrophyte vegetation.

In regard to habitats used for reproduction, all solid elements of an estuary, lake or river bottom can be used as a foundation for round goby nests including stones, rocks, parts of wood, roots of vascular plants, and even dumped waste (Sapota 2012). In contrast to European findings, **round gobies in streams such as the St. Clair River (a Great Lakes tributary and site of the first invasion colonization in North America) occur in habitats that offer cover. These include cobble substrates to 3 m depth (Jude et al. 1992), riprap, and vegetation in nearshore areas where substrates offer large interstices for refuge and spawning** (Jude and Deboe 1996; Ray and Corkum 2001). Round Goby catches are generally lower in wetland macrohabitats than in adjacent lake macrohabitats where gobies seem to prefer areas dominated by submersed aquatic vegetation (Cooper et al. 2007). Round gobies are also known to visit sandy habitats near beaches at night. This is especially true of juveniles in search of zooplankton and other small macrophytic-based prey items whereas adults are less abundant on sand substrates (Jude et al. 1992; Jude and Deboe 1996).

Round gobies may migrate to deeper water in winter (Miller 1986; as cited in Hirsch 1998). Their diet consists of micro- and macroinvertebrates including amphipods, polychaetes, chironomids, cladocerans, bivalve mollusks, and occasionally other small fish and fish eggs (Jude et al. 1992). **The Round Goby prefers shallow waters up to 3 m and they avoid surf zones** (Kornis et al. 2012). They are generally sedentary, with home ranges estimated at just 5 to 6 m or so, however there is evidence (see below) that some gobies are capable of fairly long-distance movements up to a couple km (Wolfe and Marsden 1998; Ray and Corkum 2001). Commercial shipping, however, is the main culprit that influences in-lake dispersal (Kornis et al. 2012).

Phillips et al. 2003 examined Round Goby habitat use in three tributaries to Lake Erie in Pennsylvania. Habitat preferences were similar in each of the three streams (rocky areas having moderate streamflow). An important observation was made. **Smooth, shallow bedrock areas in upstream portions of these streams were not used,** presumably because they contain fewer ledges and crevices than found in deeper, more open stream areas. Thus, shallow bedrock areas appear to act as barriers to colonization and further upstream movement by round gobies.

Additional research on habitats used by round gobies have noted their ability to perch on rocks and other substrates in shallow areas, yet flourish in a variety of habitat types that may include open sandy areas where favorite prey items (aquatic macrophytes) are abundant (Jude and DeBoe 1996; Clapp et al. 2001). This goby also has a well-developed sensory system that enhances its ability to detect water movement. This allows round gobies to feed in complete darkness, providing an advantage over other fish species in the same habitat (Wisconsin Sea Grant 2008).

In a mark-recapture study of Round Goby in three Great Lakes tributaries, Ray and Corkum 2001 estimated fish densities, site fidelity and habitat preferences over time. Perhaps not surprisingly, mean goby densities were highest in their St. Clair River site (the original area of Round Goby colonization in North America), with lower densities of small gobies (≤ 5 cm) at their Detroit River site near Peche Island (an area most recently colonized by round gobies). However, the fairly high percentage (58%) of round gobies recaptured at or near study-site release locations (Ray and Corkum 2001) indicated a strong tendency for site fidelity (for both males and females) in rock-substrate habitats as opposed to sandy habitats, with adults most active during the day than at night (likely an adaptation to avoid predation).

Wolfe and Marsden 1998 found similar site fidelity in a tagging study of 308 round gobies they conducted in Lake Michigan. With the exception of a single fish caught by an angler 2 km from its release site, Wolfe and Marsden observed all tagged-fish recaptures within 67 m of the tagging site. As for habitat preferences, Ray and Corkum 2001 found round gobies to be more abundant in rock than in sand habitats, with younger age classes more prevalent during daytime than at night (suggesting that large-sized gobies were in refugia during daylight). Although gobies were somewhat common in sand substrates in the Ray and Corkum study, they suggest that habitat complexity at rock substrates likely corresponds to an increase in refuges (accounting for the higher densities found in rocky substrates). Because juveniles seem to be more prevalent in sandy substrates, the authors hypothesized that adults may displace juveniles into sub-optimal habitats.

Discrepancies and apparent data conflicts were found among the reports of habitat preferences cited by various authors included in our review. Such differences may be reflective of local adaptations by different populations to specific habitats. However, and as noted by others (Gutowsky and Fox 2012, Kornis et al. 2012, Thompson and Simon 2015), the Round Goby exhibits high intraspecific variations in age and growth (local adaptations) that are related to site specificity and factors such as density, food, predation, competition and water quality.

Management Implications: The Round Goby shares several life-history characteristics present in successful invasive species colonizers: a tolerance for a wide range of environmental conditions, a broad diet, aggressive behavior, high fecundity, repeat spawning capabilities within a season, cavity nesting for egg protection, nest guarding by males, and a fairly large body size compared to species having a similar benthic lifestyle. These attributes have allowed the Round Goby to quickly establish populations in all of the Great Lakes and many of their tributaries. They pose a bona fide challenge for invasive species management.

The localized site fidelity of the Round Goby coupled with its preference for rocky, cobble substrates and underwater structures indicate that transport and colonization risks can be reduced or eliminated when these habitats are unavailable. Because smooth, bedrock-type areas were found to act as a barrier to Round Goby colonization and upstream range extension in one Lake Erie study, the addition of such streambed modifications (replica structures) could serve to minimize goby presence downstream of waterway projects. Such efforts may be costly and may present streambed engineering challenges. However, if technologies such as electric fish barriers are considered for Round Goby deterrence at Menasha Lock and other Fox River areas, these barriers should be effective deterrents and it may be possible to include design modifications that discourage goby presence.

In summary, the likelihood that discharges from Menasha Lock will naturally exceed the poor swimming abilities of larval round gobies, the strong preference of larval gobies to remain at the bottom of the channel during daylight hours when the lock is operational, and the preference of larval gobies to rise in the water column at night when there is no upstream current and the lock is not operational should all act synergistically and counter to any argument in support of juvenile transport at the lock. If an electric barrier is designed having the characteristics described in Savino et al. 2001, upstream movement by adult Round Goby is also precluded.

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Potential for Warping and Arcing at Proposed Menasha Lock Electrical Barrier

INTRODUCTION

Fish are uniquely sensitive to electrical currents because their muscle control is based on electrical impulses through their nervous system, and because they inhabit a conductive environment. Electrical barriers and guidance systems make use of this sensitivity. Electrical barriers involve electrical current passing from one submerged electrode (or series of electrodes) to another. When a fish is within the field, they become part of the electrical circuit with some of the current flowing through its body. This induces reactions ranging from behavioral modification to full tetany, depending on the strength of the current, voltage gradient, and pulse duration and frequency they receive.

The proposed electrical barrier at Menasha Lock is what is referred to as a "bottom-mounted barrier." This is a bit of a misnomer because electrodes would be attached to the vertical side walls of the barrier as well as the bottom. A bottom-mounted barrier allows boat traffic to proceed without obstacles while halting migration of fish through the barrier. The question to be answered in this report is what happens to the electrical field when a boat passes through the barrier? The answer depends on the size of the boat and the material it is made out of. Three-dimensional modeling is used to model the distortion of the electrical field in some of these situations.

ELECTRICAL FIELD BACKGROUND

In the absence of voltage electrical current does not flow. Electrical sources generate a voltage on a circuit and cause electrons to flow in the circuit. How many electrons flow is dependent on the voltage on the circuit and the total conductivity of the circuit. For example, a circuit with 10 volts (V) applied and a load with a total conductivity of 1 siemen (S) would have 10 amps (A) of current flowing in it. If the same 10 V were applied to a circuit that had a total load conductivity of 0.0005 S, or 500 µS, then there would be 0.005 A, or 5 mA, flowing in it.

Circuits can be made up of many different types of conductors, loads and sources. In a fish barrier, the sources are called pulse generators (or pulsers). The conductors are the wires and electrodes in the water, and the load is the water and anything in the water.

Fish normally orient parallel to the flow of water with their heads into the flow. Electric fields oriented parallel to flow are effective in stopping fish from moving upstream. The amount of electricity a fish absorbs from the water depends on its length and its orientation in the water. Electric fields oriented in other directions – i.e. perpendicular to flow or from the top of the water column to the bottom, do little to affect fish behavior because fish spend little time oriented in these directions.

BOAT USE AT MENASHA LOCK

Prior to the closure of Menasha Lock, detailed records of boat lockages at Menasha Lock were not kept. However, Smith-Root talked to the FRNSA Locks Manager Jim VanBoxtel who provided general information about the boats that used the lock prior to the closure. In summary:

- The lock is open mid-May to October 1.

- The average usage is about 1500 boats per year.
- Of the 1500 boats, about 35% are metal (conductive) hull boats, and 65% are fiberglass (non-conductive) hull boats.
- With the exception of work barges, the range of boat lengths is 14' to 32'.
- 75% of the boats that use the lock are 14'-18' in length.
- With the exception of work barges, most, if not all, of the boats longer than 18' are constructed of fiberglass.
- Personal watercraft make up about 5% of all boats that use the lock. Of this 5%, about half are self-propelled (canoe and kayak), and half are motored (jet ski or wave runner).
- The self-propelled personal watercraft currently have a path to portage around the lock when it is closed.

In addition to the pleasure craft that use the lock, there are occasional lockages of work barges. Mr. VanBoxtel said the DNR currently allows the work barges to use the locks up to 10 passes per year (one direction is considered one pass). 2 days before each pass, DNR treats the lock with rotenone. Prior to the lock closure, the usage of the lock by work barges was highly variable and depenedent on construction needs. Sometimes there was no barge lockage for two years, and other times there were more than 10 lockages per year.

Tom Radtke, the owner and GM of Radtke Contracting in Wisconsin, gave Smith-Root details on their work barges. In summary:

- They have 5 work barges.
- All 5 barges are made of steel.
- Four are used most often and are of nearly identical size: 32-ft wide by 115-ft long, 4-ft high (2-ft draft and 2-ft freeboard).
- The fifth is less commonly used and is differently sized: 30-ft wide by 100-ft long, 6-ft high (4-ft draft and 2-ft freeboard)
- They have two tug boats. One is 12-ft wide by 30-ft long, and the other is 16-ft wide by 45-ft long.
- When the shorter, 30-ft tug boat is used, both boat and barge can fit into the lock together.
- When the longer, 45-ft tug boat is used, the barge and boat must go through the lock separately. When that happens, the barge is pushed into the lock (regardless of direction) by the tug, and then pulled out of the lock by workers on each side of the lock with 20-ft push poles.
- Other methods can be used by Radtke Contracting to move the barge out of the lock if needed, such as use of paddles or a small motor.

WHEN A CONDUCTIVE BOAT ENTERS THE ELECTRICAL FIELD

When a large metallic object such as a boat or barge enters the electric field, it begins to attract the electric field in the water as it crosses the first electrode. Metal is a conductor, and steel is over 200,000 times more conductive than the water at Menasha Lock, so a metallic hull is much more effective at conducting electricity than water. While electricity will flow through all paths available, it shows a preference for the path with the highest conductivity – also known as the path of least resistance. As the metallic hull moves further into the barrier and across multiple electrodes, the strength of the electric current (in amperes) drawn from the pulse generators increases. This happens because the metallic hull presents an easier path for electric current than does the water between the electrodes. The current strength will continue to increase until the entire metal hull is over the barrier, and then as the hull begins to leave the barrier the current strength will begin to decrease back to normal.

During this scenario, the voltage being supplied by the pulsers does not change. However, the electric field near the metallic hull does. This is caused by the increase in electrical current flowing from an electrode through the water to the metallic hull and then back through the water to the return electrode for that pulse generator. The defining principle for this effect is Ohm's Law: V=I*R, where V is voltage, I is current, and R is resistivity. Resistivity is the inverse of conductivity, so when conductivity increases the resulting current also must increase in order to keep voltage constant.

The substantially increased conductivity of the metallic hull causes the orientation of the electric field in the water to change direction as a metallic hull moves across the electrical barrier. The fields perpendicular to the metallic hull increase in intensity, while the field parallel to the hull decreases in intensity. Also, a steel hull that is over 200,000 times more conductive than the surrounding water creates very little voltage change from one end of the hull to the other. As a result, the overall intensity of the field with a metallic hull in the barrier is higher, but the direction of the electric field changes so that the barrier is less effective in the immediate vicinity of the metallic hull while the boat is over the barrier. This effect is shown in Figure 1, a plan view of the electric barrier with a theoretical metallic hull barge, represented by the rectangle outline, in the center of the barrier. The colors represent the voltage in the water at a depth of 4 feet below the surface and 1 foot below the bottom of the barge (which was given a theoretical 3-ft draft in the model).

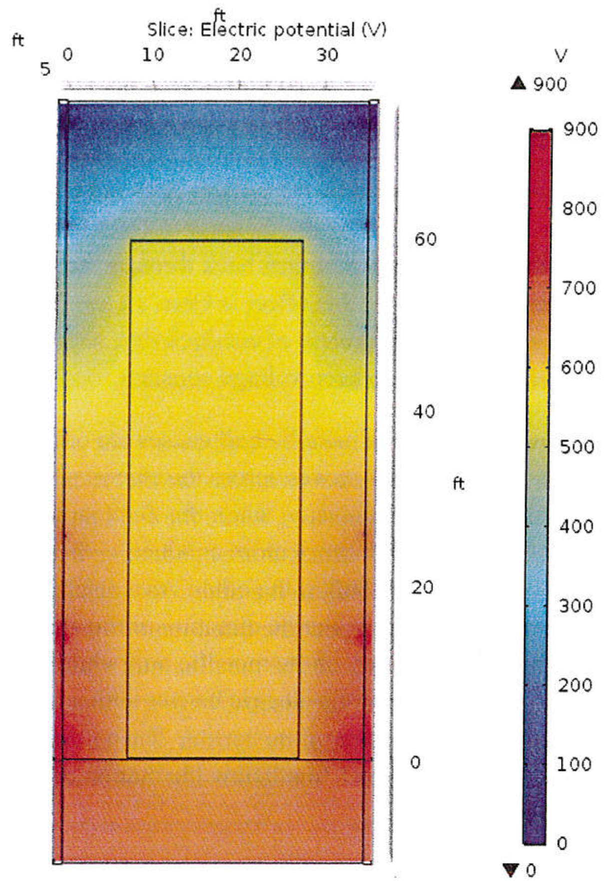

Figure 1. Voltage map (plan view) at depth 4 ft below surface (8 ft above bottom) with theoretical 60-ft by 20-ft metallic hull barge with a 3-ft draft.

The effect of the metallic hull on the electric field in the water decreases with distance from the hull. This is a key point for a barrier that is operated to deter migration of Round Goby, which migrate within 30 cm (0.98 ft) of the bottom of a channel. In the Menasha Lock barrier, the effect of the metallic hull with a 3-ft draft is abated a few feet below the bottom of the hull. Figure 2 shows the voltage potentials returning to normal at a depth of 5 feet above the floor (left, 4 feet below the hull) and unaffected at a depth of 2 feet above the barrier floor (right, 7 feet below the hull). As mentioned previously in this report, the work barges that typically use the Menasha Lock have a 2-ft draft.

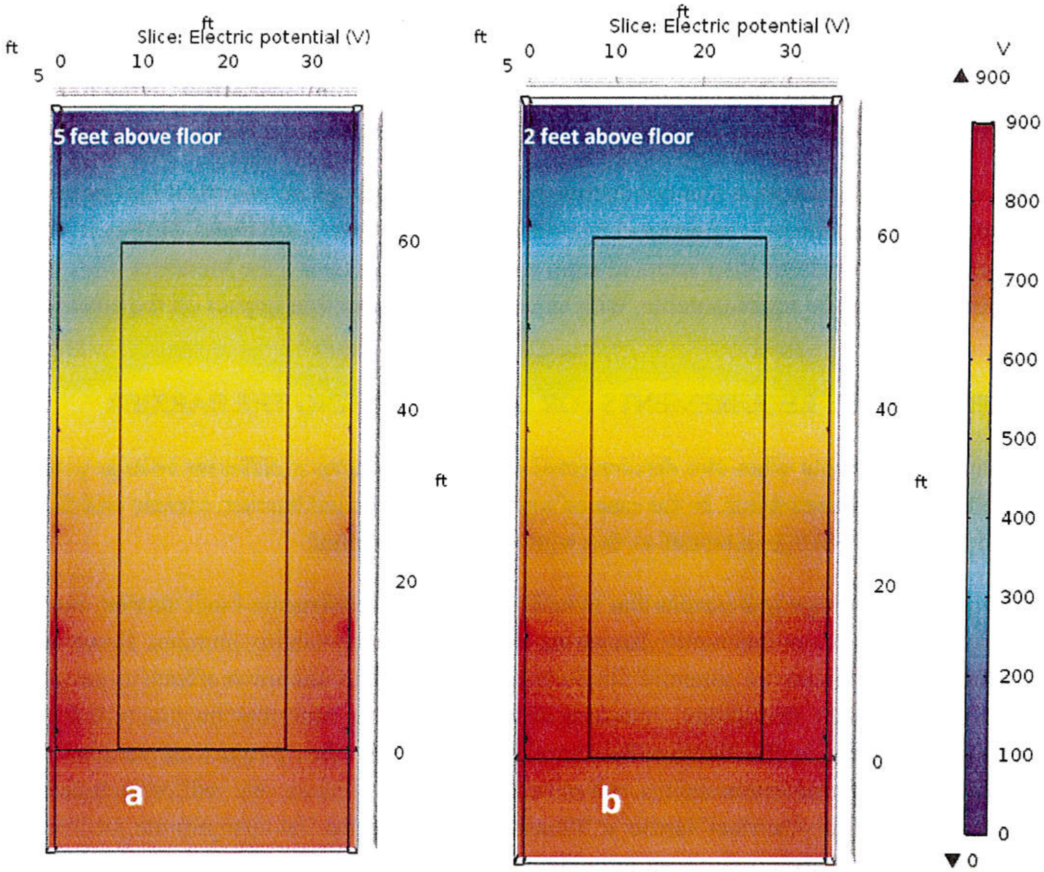

Figure 2. Voltage map (plan view) at a) depth 7 ft below surface (5 ft above bottom) and b) depth 10 feet below surface (2 ft above bottom) with theoretical 60-ft by 20-ft metallic hull barge with 3-ft draft.

The larger the hull, the greater one can expect the effect to be. Small aluminum fishing boats have little effect on the overall field of the barrier, but the effect increases with the size of the boat. For example, metal-hulled boats that draft 2 or more feet of water will have a larger effect than those that draft 2 feet or less. Similarly, a 24-ft metal-hulled boat will have a larger effect than a 16-ft metal-hulled boat. Another factor to consider is the proposed electric barrier includes electrodes running up the sides of the vertical walls. Boats with metal hulls should try to motor through the center of the barrier, as the closer a metallic hull is to the electrodes, the more the hull will affect the electric field. The magnitude of the effect a metallic hull has on a barrier depends on the size of the hull and the distance of the boat from the electrodes on the bottom or the vertical walls of the barrier.

WHEN A NON-CONDUCTIVE BOAT ENTERS THE ELECTRICAL FIELD

When a non-conductive boat enters the electrical field, the boat hull itself does not draw the electrical current as a conductive hull does. Essentially, the boat hull becomes a "void" in the electrical field that is inaccessible to fish because of the solid hull. After the boat passes any point within the barrier, the electrical field returns to normal nearly instantly. The presence of a metal propeller or small metal appurtenance (such as a fish finder transducer) may have a very minor local effect on the field that is not expected to create an opportunity for a fish to avoid the deterrent electrical field.

Through volume displacement, a non-conductive boat passing through an electrical barrier raises the water elevation. Large increases in water elevation can alter barrier effectiveness. However, the rise in water elevation due to volume displacement from a single boat accessing the Menasha Lock is expected to be so miniscule as to be immeasurable, with an equally immeasurable impact on the electrical field.

SUGGESTED SAFETY REQUIREMENTS FOR BOATS CROSSING THE BARRIER

Electrical arcing can occur when two disconnected objects or surfaces at different voltage potentials are connected by a conductive object. In the case of a pulsed DC electrical barrier, current will flow from the object with the higher voltage potential to that with the lower potential.

The combination of voltage and current that would be used for the Menasha Lock barrier, along with the selected waveform, is not an inherently dangerous electrical pulse to healthy humans. However, measures should be taken to eliminate the potential for electrical arcing due to unknown effects to people with heart conditions or pacemakers. In addition, measures should be taken to minimize the potential for people falling into or swimming in the electrical barrier without US Coast Guard-approved personal flotation devices. Physical safety measures such as rub rails, hand rails and fences, etc. will be included in the engineering design of the electrical barrier at Menasha Lock. Policies can also provide further measures of protection; some suggestions for boating policy at the electrical barrier follow:

- People may remain in boats as they cross the electrical barrier as long as they wear a USCG approved PFD.
- While crossing the electrical barrier, people should keep their arms and legs inside the boat and do not contact the water.
- Do not touch the concrete or ground beside the barrier while in or on a boat in the barrier.
- Do not attempt to get on or off a boat in the barrier.
- No metal paddles in the water.
- All metal in contact with the water must be securely bonded to the boat.
- No swimming.
- No fishing (fishing in an active electrical barrier would be a fruitless exercise).
- No craft that encourage limbs in the water, such as inner tubes, paddle boards, and petal boats.
- No metal canoes.
- We strongly recommend no plastic, PVC, rubber, or fiberglass (non-conductive) personal watercraft that can be easily capsized, such as canoes or kayaks.
- No cables or chains in the barrier. The only exceptions commercial barges and tugs where metal cables will reduce sparks between the barge and the tug. No cable or chains hanging off barges or tugs into the water.
- No anchoring.

- Use only polyrope while in the barrier and only if absolutely necessary. Wear heavy rubber gloves with no holes while handling ropes in the barrier. Wet polyrope can conduct electricity.

CONCLUSION

There is a potential for "warping" of the electrical field when metallic hull boats enter the barrier. The impact of the boat on the field – and thus the barrier effectiveness – is dependent on the size of the boat. Most metal-hulled boats that use the Menasha Lock are 18-ft in length or shorter. These types of boats have little to no effect on the operation of the barrier. Non-metallic hulled boats (plastic or fiberglass) have little impact on the effectiveness of the electric barrier, regardless of their length.

Occasionally, large, metal-hulled work barges utilize the Menasha Lock. The barges can currently use the lock under a DNR-approved rotenone treatment program that requires two days of treatment prior to a lockage. Computer simulations indicate that large work barges have the potential for making the voltage gradient equipotential in the immediate vicinity of the barge hull. This means the field would not be effective in deterring a fish that is moving through the barrier alongside and immediately adjacent to the barge. As a fish moves farther away from the barge, the voltage gradient increases. The bottom several feet of the barrier is likely to be unaffected by the passing of a metal-hulled barge above. Round Goby exclusively move along the substrate of a waterbody, utilizing the bottom one foot or less of the water column. Hence it is very likely that allowing barge traffic in the electric barrier would have no negative effect on the deterrence of Round Goby. Further study would need to be conducted to determine the risk of not deterring fish that move higher in the water column when a metal-hulled barge moves through the barrier.

Because of the inherent difference in voltage potential in an electric barrier, there is an opportunity for electrical arcing when a conductive object connects the two potentials. The resulting arc is not dangerous to a healthy human, but it should be a priority to reduce the opportunity of an arc occurring to the greatest extent possible. Physical design elements, incorporated in system design and construction, can be combined with operational and policy elements to reduce or even eliminate the opportunities for arcing to occur at the barrier.

Barrier System Response to Changes in Water Quality

INTRODUCTION

Water quality is an important factor in electrofishing and in deterrence of fish. Of water quality parameters, the parameter that has the highest impact on effectiveness of using electricity in water is conductivity (also referred to as specific conductance). The ease of collecting "spot measurements" of water conductivity is fairly high, and as a result there are multiple data sets of repeat collections of water conductivity at specific locations throughout the Fox River.

Cursory inspection of the water conductivity data reveals that water conductivity in the Fox River is highly variable. The variability of this water quality parameter can, in turn, affect the efficacy of in-water electrical fields, such as the proposed electrical fish deterrent system at Menasha Lock. The issue of how an electrical barrier is affected by changing water conductivity is addressed in detail in this report.

OHM'S LAW AND POWER TRANSFER THEORY

Documentation of the use of electricity to capture fish can be found as far back as a British patent granted to Ishan Baggs. The earliest known research conducted on the effectiveness of fishing with electricity was after World War I (McMillan 1928). The science of inducing behavioral response in fish using electricity was advanced in the 1950's and 1960's, culminating in the important text book "Fishing with electricity" (Vibert 1967).

The basic principle of how power is distributed in an electrical barrier is described by Ohm's Law, which states that the current through a conductor between two points is directly proportional to the voltage across the two points. The expression of Ohm's Law is $I = V / R$ where I is current, V is voltage, and R is resistance. In an electrical barrier, resistance is provided by the water between two electrodes. Water conductivity is an expression of the water's capability to pass electrical current. The equation for resistance is $R = d / (c*A)$, where d is length of material, c is conductivity, and A is cross-sectional area. When length and area are held constant, an increase in water conductivity decreases the resistance of the water. Taking this relationship back to Ohm's Law, when voltage is held constant, a decrease in resistance of water will increase the current in the circuit. These two equations are essential in predicting what will occur when the water conductivity in an electrical barrier increases or decreases.

In 1989, a paper on power transfer theory (Kolz 1989) led to a sharp increase in electrofishing efficiency. This concept is also the basis for the operation of electrical deterrence and guidance systems. Power transfer theory, in short, is the concept that the power transferred to a fish is a function of the ratio between the conductivity of the water and the conductivity of the fish. As the difference between the relative conductivities increases, the efficiency of the system decreases. Thus power needs to be adjusted as a function of conductivity. Power, with the typical unit of watts, is simply the product of current (in units of amps) and voltage (in units of volts).

In the case of an electrical barrier, a target voltage gradient is prescribed for an area, and electrical power, with characteristics of voltage and current, is delivered to the electrodes to generate the prescribed electrical field. The power needed to deliver this prescribed voltage gradient is dependent on the water conductivity. When conductivity changes, the power needed to maintain the prescribed voltage gradient changes by a known factor. An excellent discussion of the science behind this relationship can be found in a blog post by Dr. Jan Dean (2016). The curve in Figure 1 is taken from this blog post. The curve shows maximum efficiency around 115 µS/cm, which is the accepted average conductivity of a fish (Miranda 2009). When water conductivity is higher than 115 µS/cm, more power output is needed to maintain the prescribed voltage gradient. This is accomplished by increasing the current, measured in amps, of the output.

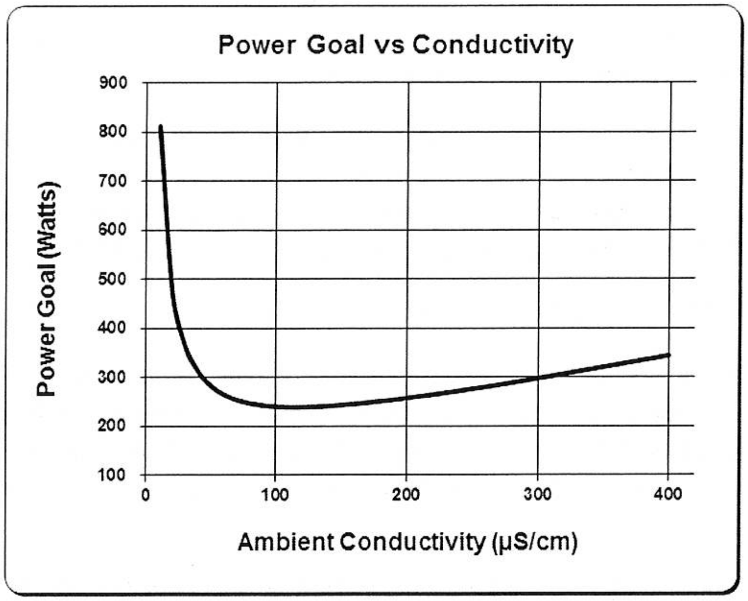

Figure 1. Electrofishing power output goal as a function of water conductivity (Dean 2016).

WATER CONDUCTIVITY AT MENASHA LOCK

Smith-Root gathered previously-collected water quality data from several sources near the Menasha Lock. The summarized information for the two nearest sources is given in Table 1.

Table 1. Water quality data collection stations and sources near Menasha Lock.

Station No.	Source	Gauge Name	Start Date	End Date	N	Min Sp. Cond.	Max Sp. Cond	Mean Sp. Cond.
						µS/cm	µS/cm	µS/cm
04084422	USGS	Little Lake Butte Des Morts at Menasha, WI	10/18/1989	11/17/1992	9	306	404	358
713002	Wisconsin DNR	Fox River – Lake Winnebago Outlet	3/30/2015	3/28/2018	49	317	513	402

The DNR data set has been collected regularly since March 2015 at Fritze Park. The proximity of this data set and the recent and ongoing collection dates make it the most relevant data set for monitoring water conductivity at Menasha Lock. A statistical analysis of the 49 measurements at this station returns a mean conductivity of 402 μS/cm with a standard deviation of 41.6. The range of collected values is almost 200 μS/cm, with a minimum observed value of 317 and a maximum observed value of 513 μS/cm.

The range of values is rather large. Simulations, to be described later in this document, evaluated water conductivities +/- 3 standard deviations from the mean, 277 and 527 μS/cm, which is expected to encompass 99.7% of the observed water conductivity at Menasha Lock. An additional simulation with environmental water conductivity of 600 μS/cm is also evaluated.

SMITH-ROOT BP-1.5 POW PULSE GENERATORS

Smith-Root BP-1.5 POW pulse generators are designed to deliver a pulsed DC current to the water column at a constant, prescribed voltage. In order to maintain this voltage, the output power needs to be adjusted to the environmental water conductivity in the barrier vicinity. This is achieved through a continuous feedback loop that adjusts output current as a function of water conductivity, maintaining the output voltage constant.

While the BP-1.5 POW pulse generators can operate independently, they are typically connected to a fish barrier telemetry and control system (FBTCS) that compiles the input and output of each pulse generator connected to the system and provides a remote or on-site user interface. In addition, the FBTCS is capable of integrating outside monitoring data, such as a water conductivity meter or water level sensor, and can automatically send instructions to the pulse generators when user-defined thresholds are met.

SENSITIVITY ANALYSIS

Using a general purpose finite element analysis software, COMSOL Multiphysics, Smith-Root conducted a sensitivity analysis of a potential Menasha Lock electrical field and, holding constant all other factors, evaluated the required power output at several water conductivities.

The result of the voltage gradient as a function of water depth is shown in Figure 2. The distance in the table is in units of feet below the water surface; the purple line is at the bottom of the barrier and the dark blue line is at the water surface. Because the power output from the BP-1.5 POW pulse generators hold voltage output constant, the results of this graph do not change with water conductivity.

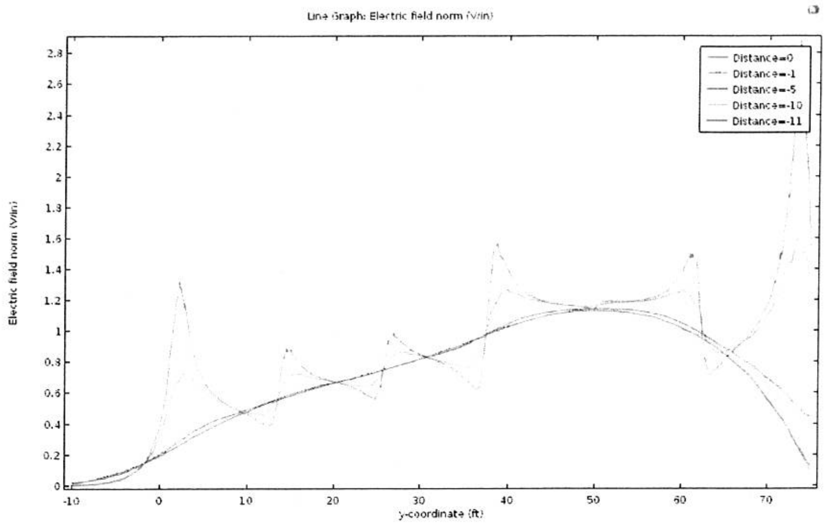

Figure 2. Characteristic COMSOL model output for Menasha Lock with multiple water conductivities.

While output voltage is constant, output current and power change as environmental water conductivity changes. This relationship is predicted by Ohm's Law, and the model output shows a generally linear relationship between conductivity, current and power, as is expected. The results are presented in Table 2.

Table 2. COMSOL model output for Menasha Lock barrier at various simulated water conductivities.

Simulated water conductivity	**Peak output voltage**	**Peak output current**	**Output power at 100% duty cycle**	**Output power at 5% duty cycle**
(µS/cm)	**Volts (V)**	**Amps (A)**	**Watts (W)**	**Watts (W)**
277 µS/cm	900	266.7	36,781	1,839.1
402 µS/cm	900	327.4	53,093	2,654.7
527 µS/cm	900	428.0	69,404	3,470.2
600 µS/cm	900	486.8	78,928	3,946.4

CONCLUSION

The conductivity component of water quality in Little Lake Butte Des Morts is relatively inconstant, thus the question of how an electrical barrier can handle a conductivity range of more than 200 µS/cm is certainly relevant. Ohm's Law and the power transfer theory describes how the electrical pulse, generated by the Smith-Root pulse generators, is distributed in the water within the electrical barrier and subsequently to fish that enter the barrier. In general, an increase in conductivity results in the pulse generators automatically increasing the output power in order to maintain the constant voltage in the electrical barrier. When the ambient conductivity always exceeds 115 µS/cm, as does the water of Little Lake Butte Des Morts, the limiting factor then becomes high values of conductivity. Thus, an electrical barrier system at the Menasha should be designed to function with the highest anticipated water conductivity in Little Lake Butte Des Morts. This maximum value of anticipated water conductivity is a variable that will be confirmed with Wisconsin DNR prior to the completion of system design.

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Scale and Effectiveness Validation of Electrical Barriers in Service

More than 70 Smith-Root-designed electrical barriers and guidance systems have been installed across the globe. Use of electricity to guide and block fish is not a new concept; alternating current (AC) barriers have been used since the 1930's and are still in use in some small rivers and streams today. The first generation of Smith-Root electrical barriers in the late 1980's built upon the principles of electrofishing and utilized safe and economical levels of pulsed direct current (DC).

Smith-Root electric barrier are custom-designed for each situation and, as such, includes a wide variety of barrier geometries, waveforms, and field strengths. For example, power output can vary from 30 W (at the Lake Seminole Fish Pond drain barrier in Georgia) to 3.85 MW at the three combined barriers in the Chicago Sanitary and Ship Canal in Illinois. In short, the objective of each barrier and guidance system is what drives the system design.

Appendix 1 presents the 44 electric barriers and guidance systems Smith-Root has designed and installed since 1999. The owners of many of these facilities elect to have Smith-Root conduct annual (or more frequent) maintenance inspections, which include verification of the electrical field in the facility, electrical tests of the pulse generators, and other facility inspection duties. These return visits to active facilities give Smith-Root the opportunity to assess the ongoing effectiveness of the electric field. The field measurements for three of these barriers are given in Figures 1 through 3. The figures demonstrate the consistency of the electrical field strength within the barrier over time. While water quality characteristics and depth are variable, the pulse generators are able to adjust to these external factors and maintain minimum voltage gradients in varying conditions. Further discussion of the mechanisms for maintaining voltage gradients in variable conditions is presented in separate report in this series.

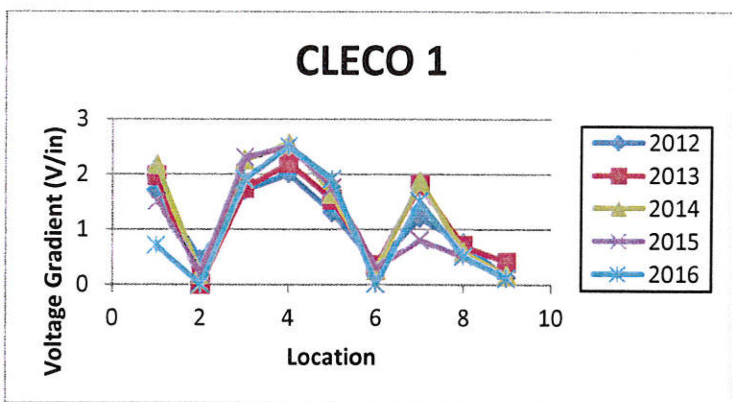

Figure 1. Measured voltage gradient at nine locations within and outside of the CLECO 1 electrical barrier in St. Landry, Louisiana.

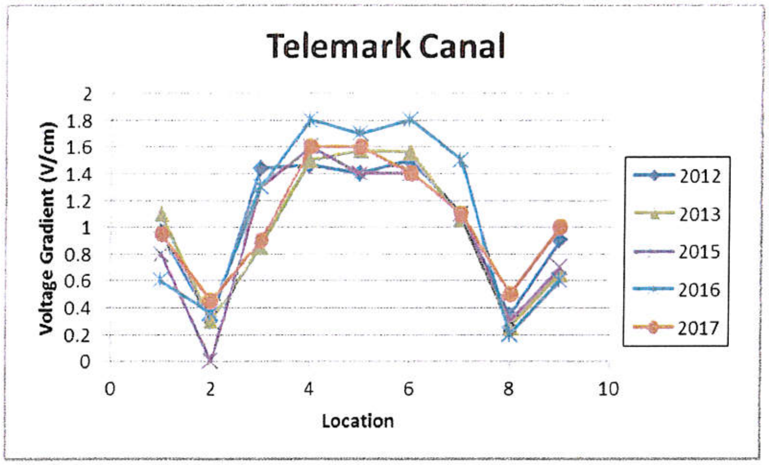

Figure 2. Measured voltage gradient at nine locations within and outside of the Kjeldal Lock/Telemark Canal electrical barrier in Telemark County, Norway.

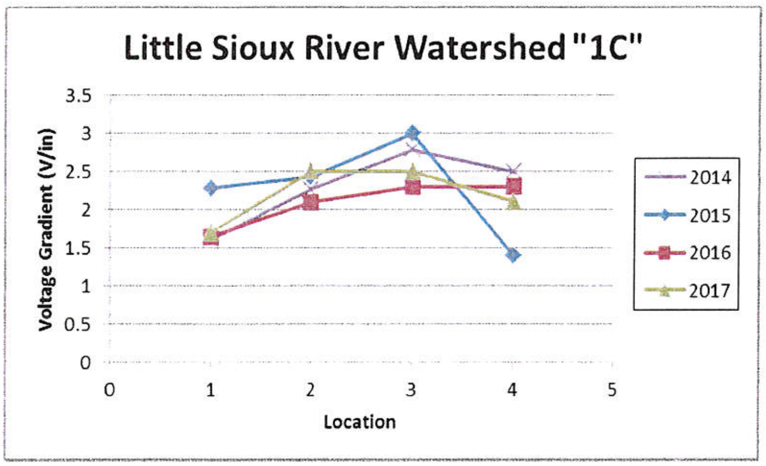

Figure 3. Measured voltage gradient at four locations within and outside of the Little Sioux River Watershed "1C" barrier near Worthington, Minnesota.

We also summarize several studies that have been conducted on installed fish barriers. All of the barriers studied are still in operation and effectively deterring upstream migration of fish.

Case Study 1 — Bottom-Mounted Electric Barrier to Deter/Guide Upstream-Moving Fish in a Hydropower Tailrace

Location – Geneva, Switzerland

Year of study – 2008

The effectiveness of a hydropower, tailrace electric barrier was evaluated in a technical report for a power generation facility at Vessy (near Geneva), Switzerland by GREN Biologie (2009). The electric deterrence array was installed in 2008, in the tailrace of this twin-turbine, annual 3 GWh hydroelectric generating station owned by Centrale Hydroelectrique de Vessy (Figure 4). During October 2008, 339 brown trout were brand-marked and released downstream of the barrier in an attempt to assess the electric barrier's efficiency at preventing fish movements into the powerhouse. The consultant's technical report (in French) was translated and approved by the power authority. Key points from their report include the following results:

"The fish, which moved upstream using a migration route situated along the left bank, did not enter the tailrace and were effectively guided along the bed of the River Arve. In fact, whether these fish were fall trout or spring barbels, a comparison of fish actually present in the tailrace to the catch in the traps of both fishways shows that the electric barrier played its role perfectly and migrating spawners did not have a propensity to wander (at a higher rate) into the tailrace."

"None of the 339 brand-marked trout put into water of the River Arve in mid-October 2008 … just downstream of the plant … were found in the tailrace one month later, while in this interval 16 of the brand-marked trout were passed by the two fishways. These results confirmed that the electric barrier demonstrated good efficiency in helping to move branded trout upstream and that none ended up becoming trapped at the foot of the hydroelectric plant."

"Despite the capacity of the tailrace to provide fish habitat, very few fish were found during electrofishing. The effectiveness of the electric barrier system explains the insignificant presence of fish observed in the tailrace compared to the much higher fish numbers found in the River Arve at a point directly proximal to the hydropower station."

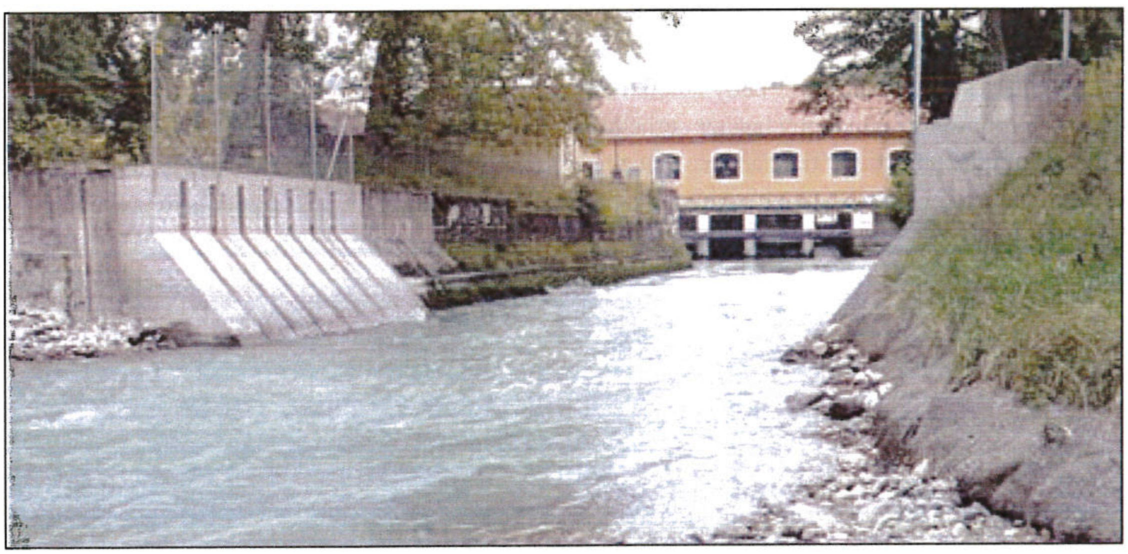

Figure 4. The tailrace electrical deterrence array at the Vessy (Switzerland) hydroelectric power plant. A series of seven electrode cables can be seen housed within the special, non-conductive concrete slab that was installed to run across the river bottom from left to right bank, thus providing full deterrence capabilities across the entire stream without being affected by floating debris. The barrier successfully deterred fish from moving upstream from the River Arve into the tailrace and powerhouse.

<u>*Case*</u>

Study 2 – Deterrence/Guidance of Upstream-Moving Anadromous Fish at a Hydropower Tunnel Outlet

Location – Helle, Norway

Year of study – 2014

In 2013, a Smith-Root designed vertical electrode barrier system was installed at the outlet of the power tunnel at the Rygene Power Plant on Nidelva (River Nid) in southern Norway (Figure 5). The purpose of the barrier was to deter upstream-migrating Atlantic salmon and sea trout from migrating up the power tunnel in favor of continuing up Nidelva to the fish ladder at Rygene Dam. When operation of the barrier began in 2014, the power plant owner commissioned a study of the effectiveness of the barrier. The study authors installed video cameras inside the power tunnel immediately upstream of the barrier, and in the fish ladder at Rygene Dam. A comparison of the numbers of fish that passed the cameras at the two locations was made to determine the efficiency of the electric barrier.

During the 131-day study period in 2014, a total of 10 migratory fish passed the cameras inside the power tunnel. This represents 0.7% of the total anadromous run that year, leading to a 99.3% efficiency rate for the electric barrier. The study authors concluded "the electric fish barrier therefore functioned as intended" in 2014.

While 100% deterrence wasn't achieved at this location, it is important to note that 100% deterrence was not the objective of the system. The objective of the system was to create a substantial reduction in the number of misdirected anadromous fish. The tunnel exit is logistically a difficult location, requiring construction directly into a bedrock outcrop. The maximum length of the barrier (from downstream to upstream parallel with the outlet flow) is about 5 m, and the Atlantic salmon in Nidelva can grow to lengths of 1 m, for a barrier length to body length ratio of 5:1. In contrast, the barrier length to body length for the proposed Round Goby barrier at the Menasha Lock is around 100:1. This difference reflects the difference in the objective of the barrier – the objective of the Nidelva barrier is to substantially reduce upstream passage in the tunnel, while the objective of the Menasha Lock barrier is to prevent all upstream passage.

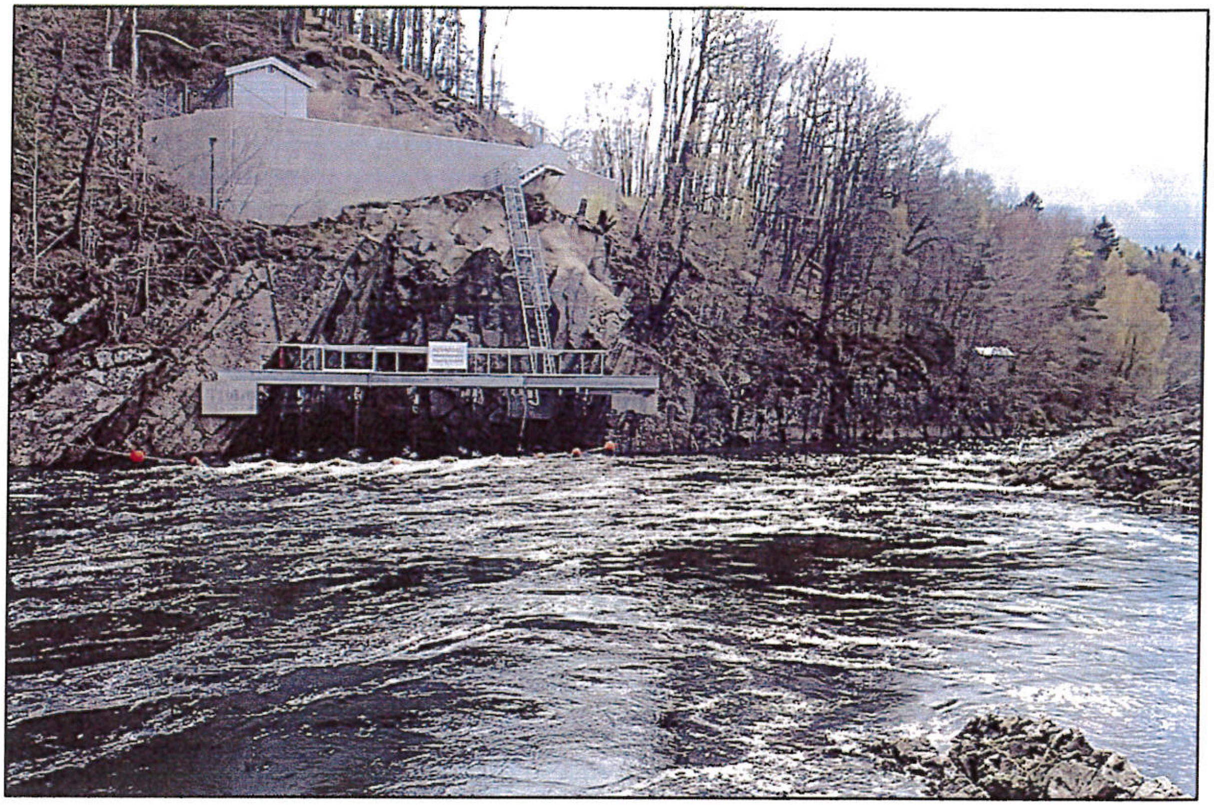

Figure 5. The electrical barrier at the outlet of the Rygene Power Plant power tunnel on Nidelva in southern Norway. Three vertical rows of electrode cables are affixed to the overhead steel structure and the tunnel floor, presenting the electrical deterrent field uniformly at all depths in the water column. The barrier has been demonstrated to successfully deter anadromous fish from migrating upstream in the power tunnel, allowing them to continue their upstream migration in the river channel.

Case Study 3 – Deterrence of Upstream-Moving Fish in the Chicago Sanitary and Ship Canal

Location – Romeoville, Illinois

Year of study – 2004

The world's largest electric fish barrier system was first installed in the Chicago Sanitary and Ship Canal in the early 2000's (Figure 6). This Canal is 60 m wide and up to 9 m in depth, having water velocities up to 0.8 m/s and reverse flows of about 0.3 m/s. There are presently three, bottom-mounted electrode arrays installed in the Canal (each spanning its full width and depth) with plans to add a fourth in the near future. The project's goal is to ensure that invasive carp species do not reach or colonize the Great Lakes. Post-installation studies of barrier effectiveness used common carp species as surrogates. Of the 130 tagged and released downstream of the original demonstration barrier, only one transmitter was located upstream of the barrier during the study; a single transmitter that never changed position, suggesting a dead fish swept upstream by a passing barge.

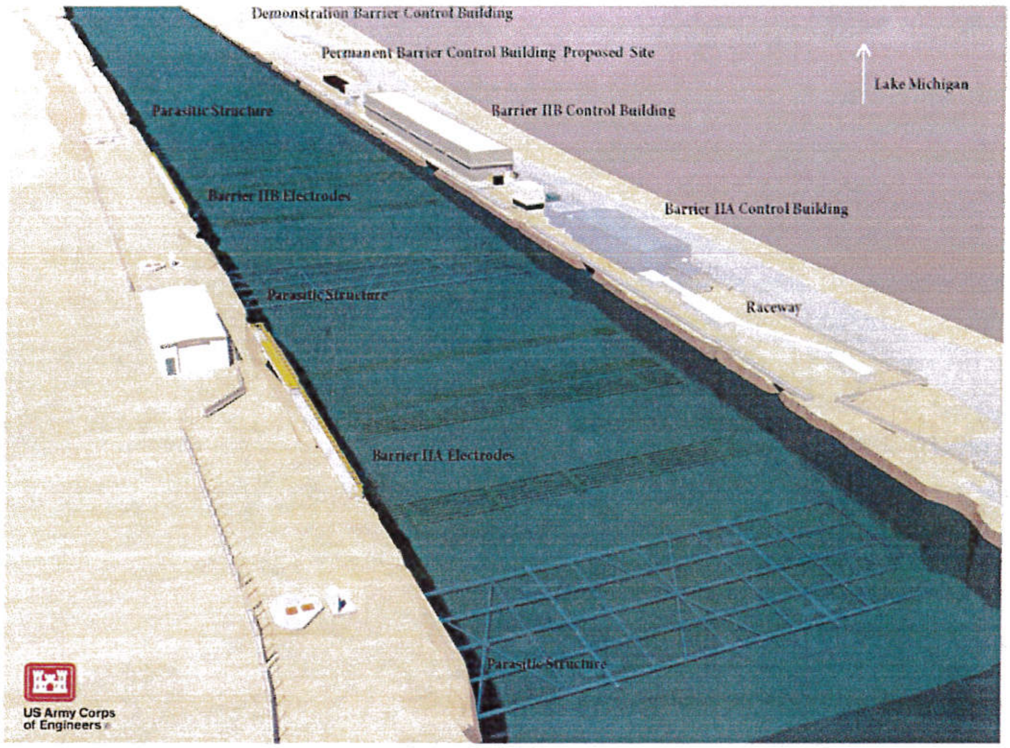

Figure 6. Schematic of a portion of the electrical barriers in the Chicago Sanitary and Ship Canal near Chicago, Illinois. These barriers are the "last line of defense" against Asian carp, present in the canal and the Des Plains River, establishing a population in the Great Lakes. Since the installation of the first barrier in the canal in 2002, Asian Carp have not advanced their population beyond this series of barriers.

Other Findings: A host of additional published studies and reports have evaluated the effectiveness of electric barriers in either blocking or guiding the movements of fish for various resource management-related needs. Several are annotated here for possible future examination and reference:

- Maceina et al. 1999 (Grass Carp Containment Goal): "After the electric barrier was in place, no verified escapes occurred."
- Swink 1999 (sea Lamprey Blockage Goal): "No unmarked and none of the 1,194 tagged sea lamprey were found above the electric barrier."
- Savino et al. 2001 (Downstream Guidance Evaluation): "The only marked Round Goby found below the electric barrier were dead."
- Verrill and Berry 1995 (Invasive Carp Blockage Goal): "None of 1,600 tagged fish were among the 3,367 examined above the barrier."

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APPENDIX

List of Smith-Root barriers constructed since 1999

Year Constructed	Project Name	Project Type	Location	Client
2017	Mill Pond Dam Removal Temporary Electrical Barrier	Temporary main channel barrier	Sullivan Creek Metaline Falls, Washington	Seattle City Light
2016	Franciolini Power Plant Electrical Guidance System	Downstream guidance	Fiume Ecino Ancona, Italy	ENEL SpA
2015	Illinois Lake "Site 6C"	Main channel barrier	Illinois Lake outlet Round Lake, Illinois	Minnesota Department of Natural Resources
2015	Goose Creek Electrical Barrier	Main channel barrier	Goose Lake outlet Albert Lea, Minnesota	Shell Rock River Watershed District
2015	Albert Lea Lake Outlet Electrical Barrier	Lake outlet barrier	Shell Rock River Albert Lea, Minnesota	Shell Rock River Watershed District
2014	Rygenefossen Hydroelectric Outlet Tunnel	Tailrace barrier	Nidelva Arendal, Norway	Agder Energi
2014	Little Sioux River Watershed "Site 1C"	Main channel barrier	Agricultural ditch Brewster, Minnesota	Minnesota Department of Natural Resources
2013	Lost Island Lake Electric Barrier	Lake inlet barrier	Lost Island Lake Ruthven, Iowa	Iowa Department of Natural Resources
2013	Lake Okoboji Outlet Electric Barrier	Lake outlet barrier	Lower Gar Lake Milford, Iowa	Iowa Department of Natural Resources
2012	Gunnison Tunnel Electric Barrier	Downstream guidance	Gunnison River Montrose, Colorado	Delta-Montrose Electric Association
2012	Telemark Canal	Canal barrier	Kjeldal Lock canal Telemark County, Norway	County Governor of Telemark
2011	Mountain Bayou Lake Electric Barrier	Lake barrier	Mountain Bayou Lake Bunkie, Louisiana	CLECO
2011	Rainey Creek Electric Barrier	Main channel barrier	Rainey Creek Swan Valley, Idaho	Idaho Department of Fish and Game
2011	Chicago Sanitary & Ship Canal Electric Dispersal Barrier 2B	Main channel barrier	CSSC Romeoville, Illinois	U.S. Army Corps of Engineers

2010	Green Lake Electric Barrier	Lake outlet barrier	Green Lake Spicer, Minnesota	Minnesota Department of Natural Resources
2010	Pine Creek Electric Barrier	Main channel barrier	Pine Creek Swan Valley, Idaho	Idaho Department of Fish and Game
2010	Wedge Creek Electric Barrier	Lake inlet barrier	Wedge Creek Albert Lea, Minnesota	Shell Rock River Watershed District
2010	White Lake Electric Barrier	Lake inlet barrier	White Lake Albert Lea, Minnesota	Shell Rock River Watershed District
2009	Fulda First Lake Electric Barrier	Lake outlet barrier	Fulda First Lake Fulda, Minnesota	Minnesota Department of Natural Resources
2009	Mud Lake / Pickerel Lake Electric Barrier	Lake outlet barrier	Pickerel Lake Albert Lea, Minnesota	Shell Rock River Watershed District
2009	Palisades Creek Electric Barrier	Main channel barrier	Palisades Creek Irwin, Idaho	Idaho Department of Fish and Game
2008	Vessy Hydropower Barrier	Tailrace barrier	River Arve Geneva, Switzerland	Services Industriel de Geneva
2006	Arrowwood National Wildlife Refuge Electrical Barrier	Main channel barrier	James River Jamestown, South Dakota	U.S. Fish & Wildlife Service
2006	Chicago Sanitary & Ship Canal Electric Dispersal Barrier 2A	Main channel barrier	CSSC Romeoville, Illinois	U.S. Army Corps of Engineers
2005	Lake Maria Electric Barrier	Main channel barrier	Lake Maria outlet Slayton, Minnesota	Minnesota Department of Natural Resources
2004	Lower Saint Mary Lake	Temporary downstream barrier	Lower St. Mary Lake Babb, Montana	U.S. Bureau of Reclamation
2004	Abernathy Fish Technology Center	Main channel barrier	Abernathy Creek Longview, Washington	U.S. Fish & Wildlife Service
2003	Blackfoot River	Main channel barrier	Blackfoot River Conda, Idaho	Idaho Department of Fish and Game
2003	Karn/Weadock Generating Complex	Cooling water tailrace barrier	Saginaw River Hampton Township, Michigan	Consumers Energy
2003	Quinault National Fish Hatchery	Main channel barrier	Cook Creek Humptulips, Washington	U.S. Fish & Wildlife Service
2003	Eagle Creek National Fish Hatchery	Main channel barrier	Eagle Creek Estacada, Oregon	U.S. Fish & Wildlife Service

2002	Townshend Dam	Main channel barrier	West River Townshend, Vermont	U.S. Army Corps of Engineers
2002	Lake Wohlford Water Intake Barrier	Reservoir water intake downstream barrier	Lake Wohlford Escondido, California	City of Escondido, California
2002	Battle River Generating Station Electrical Barrier	Cooling water tailrace barrier	Battle River Forestburg, Alberta	ATCO Power
2002	Chicago Sanitary & Ship Canal Electric Dispersal Barrier 1	Main channel barrier	CSSC Romeoville, Illinois	U.S. Army Corps of Engineers
2001	Howard Lake	Lake outlet barrier	Howard Lake Howard Lake, Minnesota	Rice Creek Watershed District
2001	Round-Rice Bed Wildlife Management Area	Lake outlet barrier	RRBWMA Garrison, Minnesota	Minnesota Department of Natural Resources
2001	Ocqueoc River	Main channel barrier	Ocqueoc River Ocqueoc Township, Michigan	U.S. Fish & Wildlife Service
2000	Shiawassee River	Temporary downstream barrier	Shiawassee River Argentine Township, Michigan	United States Geological Survey
2000	Quilcene National Fish Hatchery	Main channel barrier	Quilcene River Quilcene, Washington	U.S. Fish & Wildlife Service
1999	Beeston Hydropower Plant	Tailrace barrier	River Trent Nottinghamshire, England	United Utilities
1999	Pere Marquette River	Main channel barrier	Pere Marquette River Custer Township, Michigan	U.S. Fish & Wildlife Service

American Fisheries Society Symposium 26:171–182, 2001

Use of Electrical Barriers to Deter Movement of Round Goby

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Abstract.—An electrical barrier was chosen as a possible means to deter movement of round goby *Neogobius melanostomus*. Feasibility studies in a 2.1-m donut-shaped tank determined the electrical parameters necessary to inhibit round goby from crossing the 1-m stretch of the benthic, electrical barrier. Increasing electrical pulse duration and voltage increased effectiveness of the barrier in deterring round goby movement through the barrier. Differences in activity of round goby during daytime and nocturnal tests did not change the effectiveness of the barrier. In field verification studies, an electrical barrier was placed between two blocking nets in the Shiawassee River, Michigan. The barrier consisted of a 6-m wide canvas on which were laid four cables carrying the electrical current. Seven experiments were conducted, wherein 25 latex paint-marked round goby were introduced upstream of the electrical barrier and recovered 24 h later upstream, on, and downstream of the barrier. During control studies, round goby moved across the barrier within 20 min from release upstream. With the barrier on and using the prescribed electrical settings shown to inhibit passage in the laboratory, the only marked round goby found below the barrier were dead. At reduced pulse durations, a few round goby (mean one/test) were found alive, but debilitated, below the barrier. The electrical barrier could be incorporated as part of a program in reducing movement of adult round goby through artificial connections between watersheds.

The round goby *Neogobius melanostomus* is a Great Lakes nonindigenous fish that was first recorded in the St. Clair River in 1990 (Crossman et al. 1992; Jude et al. 1992). Round goby are small, benthic fish that generally prefer cobble/rock or macrophyte-dominated substrate (Jude and DeBoe 1996). Round goby are primarily benthivores, usually eating molluscs, aquatic insects, and other aquatic invertebrates (Jude et al. 1995, French and Jude in press). The zebra mussel *Dreissena polymorpha*, another nonnative species that has colonized throughout the Great Lakes, provides a ready and plentiful food source. Consequently, round goby have moved quickly throughout the Great Lakes region (Charlebois et al. 1997). They have now entered the Illinois Water System, Chicago, Illinois, an artificial connection between Lake Michigan and the Mississippi River drainage, and are moving inland from Lake Michigan (Charlebois et al. 1997).

Some evidence suggests that round goby could compete with or displace native fish (Jude et al. 1995; Janssen and Jude in press). Round goby observed in the laboratory were extremely aggressive and can directly displace mottled sculpin *Cottus bairdi* (Dubs and Corkum 1996). Populations of mottled sculpin and logperch *Percina caprodes* have declined dramatically in areas colonized by round goby (Jude et al. 1995), possibly from competition for space or food or disruption of spawning. Entry of round goby into the Illinois Waterway System could threaten many other native species particularly as this introduced species enters the Mississippi River drainage (Charlebois et al. 1997). Zebra mussels entered the Mississippi River through this connection with major economic and ecological consequences (Miller and Payne 1997; Morton 1997), and therefore, management agencies are interested in deterring further introductions of

nonindigenous species through this connection (Charlebois et al. 1997).

Although most nonindigenous introductions of fishes have occurred through other methods (primarily stocking, bait release, and aquarium release), the spread of these fish into neighboring waterways has been enhanced via artificial connections (irrigation and boat canals) (Fuller et al. 1999). In some cases, fish native to the United States (such as blacktail shiner *Cyprinella venusta*, brassy minnow *Hybognathus hankinsoni*, comely shiner *Notropis amoenus*, brindled madtom *Noturus miurus*, flathead catfish *Pylodictis olivaris*, Atlantic needlefish *Strongylura marina*, and white perch *Morone americana*) have expanded their range through canal systems (Fuller et al. 1999). A number of clupeids (blueback herring *Alosa aestivalis*, skipjack herring *Alosa chrysochloris*, alewife *Alosa pseudoharengus*, and gizzard shad *Dorosoma cepedianum*) have entered the Great Lakes through a variety of canals (Fuller et al. 1999). To prevent further expansions of fish populations through canal systems, methods need to be developed to prevent movement of fish (native or nonnative to the United States) in either direction within these unnatural connections between watersheds.

Among possible control alternatives in the Chicago Waterway, the U.S. Army Corps of Engineers and U.S. Fish and Wildlife Service concluded that an electrical barrier would be most feasible and effective in the first part of an integrative approach to preventing fish movement through an artificial connection between watersheds (Keppner and Theriot 1997). Unfortunately, round goby have now moved beyond the original barrier site in this case, but managers are still interested in developing a test barrier to prevent additional fish movement through the site and will use information on round goby in determining their overall management scheme. Researchers and managers acknowledge that any one program or method is unlikely to be 100% effective in preventing fish movement through a canal, but even slowing down the migration of nonindigenous fish could have strong economic benefits. A first step in the management program would be to develop a barrier that would prevent a large majority of fish from crossing. Through time, additional methods to complement the original barrier would increase the likelihood of preventing fish movement through the canal. Such barriers would have global applications wherever canals have connected previously separate watersheds.

Electrical barriers have been used to guide fish into specific areas. For example, chinook salmon *Oncorhynchus tshawytscha* were guided into traps for assessments (Palmisano and Burger 1988). Electrical barriers can prevent fish (such as sea lamprey *Petromyzon marinus*) from moving upstream against the current—they can be stunned and float downstream from the area of concern (Swink 1999). However, little is known about round goby migration and behavioral responses to electrical barriers (Charlebois et al. 1997). As round goby are a current nonindigenous species of interest, our objective was to determine whether a benthic, electrical barrier could be effective in deterring passage of round goby through a waterway. We used a series of laboratory tests to quickly determine appropriate electrical settings that affected round goby behavior and a set of field tests to verify laboratory results over a longer time period and in a larger and more open setting.

Methods

Laboratory Study

Round goby were collected from the St. Clair River using hook and line. They were held in well aerated, oval (190 L) tanks with a flow-through, well-water system (12°C) on a 12 h light:12 h dark cycle. Conductivity was 1030 μS. Round goby were fed an alternating diet of zebra mussels and rainbow trout *Oncorhynchus mykiss* eggs. Shelters such as PVC pipe were placed in each tank to provide cover; tanks were shaded.

In pilot studies, round goby did not move in shallow, long tanks or in still water as they apparently reacted to movement by researchers setting up or observing a test. Therefore, a deeper tank with a more disturbed water surface was used for testing. Laboratory studies were conducted in a donut-shaped tank (2.1-m outer diameter, 0.9-m inner diameter, 0.9-m deep), lined with black plastic (Figure 1). The test tank had a water flow-through system to maintain water temperatures (12°C). An electric outboard motor placed in the tank was used to generate low (about 0.1–0.3 m/s) flow rates over the electrodes. A screen placed in front of the motor prevented round goby from moving in an upstream direction.

A benthic, electrical barrier developed by Smith-Root, Inc. was placed opposite the motor in the tank. Three electrodes were positioned parallel to each other; each electrode was placed along the

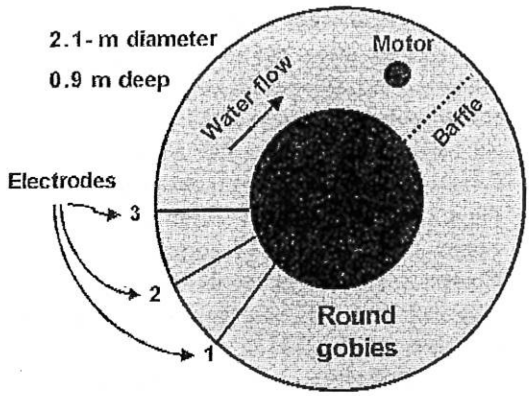

Figure 1. Diagram of laboratory test tank with location of electrodes, electric outboard motor, baffle, and initial placement of round goby.

inside walls and bottom of the tank. Each electrode could be controlled independently to provide a gradual or a sharp gradient of electricity. The gradient of the electrical field was mapped using voltage meters (EFP-2 Electric Field Probe by Smith-Root, Inc.; reference to trade names or manufacturer's does not imply U.S. Government endorsement). This barrier provided electrical current to the total water column. We did not test voltages greater than 100 V because members of the Chicago Sanitary and Ship Canal Aquatic Nuisance Species Dispersal Barrier Advisory Panel recommended that voltages applied to the barrier remain as low as possible and should not exceed 100 V to minimize potential for human injury in instances of accidental immersion near the barrier.

In canal systems, we would like to prevent movement of species downstream as well as upstream. As downstream barriers may be more difficult to achieve, we used the more conservative approach and released round goby upstream of the barrier. To start a test, a group of five round goby was measured (nearest mm, total length, TL) then released in front of the screen (in front of the motor). A video camera positioned above the electrodes filmed the behavior of round goby for the 120-min long test. Generally, if fish had adapted to test conditions in pilot studies they moved within the first 2 h of viewing. No food was available in the test chamber. Tanks were checked about three times an hour; round goby that were stunned on an electrode were removed. At the end of 2 h, round goby were removed and placed in another holding tank. At least two sets of five round goby were tested for each set of electrical parameters and controls (no electrical current). Naive (untested) round goby were used unless otherwise noted.

Behaviors were analyzed by observing the videotapes. The number of attempts and successes by round goby in crossing each active electrode was recorded. Repels were defined as a round goby approaching (entering camera's field-of-view) or crossing an electrode, turning, and moving back out of the field-of-view. Round goby that successfully crossed the electrical barrier were termed 'pass throughs.' Stuns were round goby that stayed in the electrical field until they rolled over and floated downstream or were removed. We removed all stunned fish during their occurrence in the test rather than allow them to remain in the electrical field until death.

To determine if changes in nocturnal activity changed repel rate of round goby, a set of tests was run under dark conditions. The lighting schedule of round goby in holding tanks was altered for at least 2 weeks before testing such that the 12-h dark cycle occurred from 6:00 a.m. to 6:00 p.m. A night vision scope (American Eagle Miniature Pocketscope, model 603 C, Night Vision Equipment Company) was attached to the video camera. This device allowed viewing of round goby under low-light conditions (<0.001 μmol s^{-1} m^{-2}), but also reduced the field of view of the camera by about one-third. As we had observed that most round goby traversed the barrier along the outside wall, we focused the video camera on the area between the first and second electrode along the outer wall.

To efficiently determine what factors were most important in causing a response in round goby, we set up a series of tests. Because round goby often appear to demonstrate erratic behavior, we needed to first determine if we could observe differences in behavior with and without an electrical field present. We also wanted to know if fish retained knowledge of the electrical field and therefore compared responses of naïve controls to experienced controls (tested previously in electrical fields). Other variables tested included water velocity (0.1–0.3 m/s), pulse frequency (0, 2–30 Hz), pulse duration (0, 0.05–5 ms), voltage (0, 70, 100 V), and day or night responses. A complete matrix of tests with all possible combinations of variables would have yielded an unreasonable number of tests to complete. Therefore we grouped variables in a series of tests and provided separate analyses for each of these series.

The number of repels-to-attempts ratio was analyzed with the odds ratio statistic generated in a binary logistic regression model (Proc Logistic, SAS 1995). The odds ratio was computed by exponentiating the slope of the regression model. The odds ratio in this study described the change in odds of repelling based on a test variable. If significant, the odds of repelling increase by the generated odds ratio for each unit increase in the test variable. Because we could not determine which attempts were conducted by different individuals in a group of round goby, we measured the total number of repels and the total number of attempts per test (or group of fish). Generally, the logistic analyses sum attempts among replicates. However, to avoid biasing our results with replicates with more active fish, we determined the average number (rather than the total number) of repels and attempts among replicates in each treatment for use in the model. This procedure provides a more accurate measure of the ratio of repels-to-attempts but reduces sample size of attempts used in the model. Analysis of variance (ANOVA) was used to compare differences in number of attempts to cross the electrical barrier and the total lengths of round goby used in each set of tests.

Field Study

After developing appropriate settings for the electrical barriers, small-scale field studies were developed to test the effectiveness of the electrical barrier under field conditions. A test site was selected on the Shiawassee River, near Argentine, Michigan. The stream section used was about 20 m across and 0.5–1.0 m deep with a sand bottom and occasional macrophyte beds. The bank was well defined in a straight section more than 20 m long. Tests were conducted during 20 August 1998–9 September 1998 when water temperatures ranged from 21 to 25°C, dissolved oxygen ranged 10.2–13.7 mg/L, and conductivity was 570 μS. Water depths over the barrier were initially about 45 cm (20 August 1998 through 31 August 1998) then dropped rapidly to about 15 cm depth (2 September 1998 through 9 September 1998). Water velocity (0.3–0.5 cm/s, range) was slow directly upstream and downstream of the barrier.

The electrical barrier consisted of four braided-wire cables as electrodes, secured to a canvass sheet (about 6 m wide), evenly spaced and parallel to each other along the length of the canvass (at least 22 m long). The canvass was placed across the width of the stream and up each bank. One end was attached to electrical power. Warning signs and float lines were placed upstream and downstream from the site. To prevent movement of fish into or out of the test area, block nets (7-mm bar mesh, 2 m high, two layers) were placed 9 m above and below the barrier, tied to stakes, and the bottom edge buried in sediment and rock.

Round goby were collected by seine from locations near the field site. They were held temporarily in a large, aerated tank, placed in the stream to maintain stream water temperatures. Two hours before testing, round goby were anesthetized (MS-222), measured (nearest mm), and held in a small, aerated tank until the test. At this time, each group of round goby was uniquely tagged by latex paint injections of different color combinations under dorsal scales (Kelly 1967; Hill and Grossman 1987). To begin a test, 25 round goby were released about 9 m above the electrical barrier. Round goby were recovered after a test 24 h later to determine the number above and below the barrier. Recovery methods for finding round goby after release included (1) repeated 'kick-seining' with a small bag seine (3-m x 1-m dimensions and 7-mm bar mesh, Jude and DeBoe 1996)——two people pulling the seine and one person in front of the seine kicking the substrate such that the round goby dart up and into net, and (2) walking along and on the white canvas barrier looking for stunned or dead animals before and after kick-seining.

In a control test, we first documented if round goby would typically cross the barrier within 24 h of release upstream. After the control test, another group of round goby was tagged with a different color and again placed above the barrier. Movement downstream and through the electrical barrier was monitored with the electrical barrier energized. Presence of dead or stunned round goby was monitored by seining 24 h after release and by visual inspection throughout the test. Location and movement of marked goby from previous tests were noted in subsequent trials as well. The electrical field during tests was measured with a voltage meter (EFP-2 Electric Field Probe by Smith-Root, Inc.).

Results

Laboratory

Round goby reacted to the electrical barrier but not to the range in water velocities tested (Figure 2). The odds ratio did demonstrate that signifi-

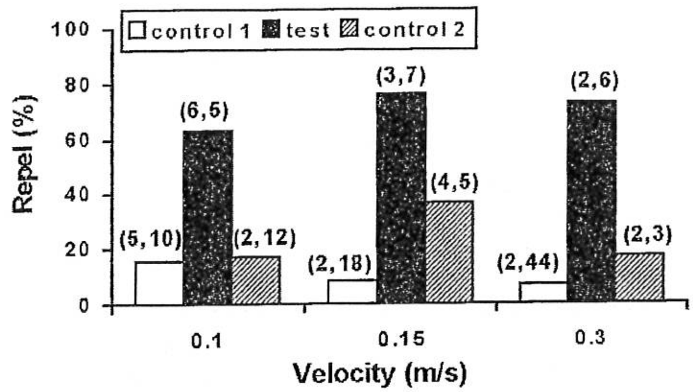

Figure 2. The percentage of round goby that were repelled from crossing the electrical barrier under laboratory conditions at each water velocity (m/s) and test condition. The number of tests and the average number of attempts per test are shown respectively in parentheses. Test conditions were: *control 1* refers to naive round goby controls (0 V) that had never gone through testing; *test* refers to round goby that were tested at 70 V (5-ms-pulse durations and 2–3-Hz-pulse frequencies); and *control 2* refers to experienced round goby controls (0 V) that had been previously tested once.

cantly more attempts to cross the barrier were repelled in tests with the barrier operating at 70 V (5 ms pulse durations and 2–3-Hz pulse frequencies) than those 'repelled' in controls (Test versus Controls, Table 1). Water velocity had no significant effect on round goby behavior in either tests or controls. Naive controls (shown as *control 1* in Figure 2) that had not been tested previously did not differ in repel rates from experienced controls (*control 2*) that had been tested previously (Odds ratio overall model: χ^2 = 2.70, 2 df, P = 0.26). Fish in five tests (one in *control 1*, three in tests at 70 V, one in *control 2*) showed no attempts to cross the barrier and were not used in the analyses. The total number of attempts to cross the barrier did change with test condition (ANOVA, $F_{8,22}$ = 3.93, P = 0.005). The number of attempts to cross the barrier was significantly higher with naive round

Table 1. Odds-ratio analyses using binary logistic models. Chi-squares for overall models based on -2 Log Likelihood statistic; χ^2 for individual tests based on Wald χ^2 (SAS 1995). An asterisk (*) designates significance at P < 0.05.

Test	Slope (SE)	Odds ratio	χ^2	P
	Test vs. controls (Figure 2)			
Overall model			27.47 (2 df)	0.0001*
Test vs. controls	0.04 (0.01)	1.04	21.70 (1 df)	0.0001*
Water velocity	−3.11 (3.22)	0.04	0.93 (1 df)	0.33
	Pulse frequency and duration (Figure 3)			
Overall model			7.47 (2 df)	0.02*
Duration	0.38 (0.17)	1.46	4.90 (1 df)	0.03*
Frequency	0.05 (0.05)	1.05	0.97 (1 df)	0.32
	Voltage during day (Figure 4)			
Overall model			4.02 (1 df)	0.04*
Voltage	0.02 (0.01)	1.02	3.45 (1 df)	0.06
	Voltage at night (Figure 4)			
Overall model			17.82 (1 df)	0.0001*
Voltage	0.04 (0.01)	1.04	15.86 (1 df)	0.0001*

goby (*control 1*) than with either round goby in the tests with the barrier operating at 70 V or in *control 2* (those tested previously). Average length of round goby used did not differ with test condition in this or any of the following laboratory comparisons (ANOVA, $P > 0.10$).

The effects of pulse duration and pulse frequency on round goby repel rates were explored at 70 V in the next set of tests (Figure 3). Three sets of controls were used in the analyses to provide the balance required in the statistical analyses (as shown in Figure 3). Only pulse duration was significant in the model (Table 1). In general, more round goby were repelled as pulse duration increased from 0.05 to 5 ms. We observed one aggressive interaction in this set of tests (0.5 ms, 2 Hz) in which a round goby nipped another and pushed it into the electrical field. Fish in three tests (one control, two tests) did not attempt to cross the barrier and were not used in the analysis. Round goby that were not repelled after an attempt were either stunned or passed through the barrier. No significant differences were found for the number of stuns ($\chi^2 = 2.41$, 2 df, $P = 0.30$) with changes in pulse duration and pulse frequency; an average of 12% of fish were stunned (1–23%, 95% confidence interval) when the electrical barrier was on. The percent of fish passing through the barrier was inversely related to the percent of fish repelled and also showed significant differences in the pulse duration and pulse frequency model ($\chi^2 = 10.66$, 2 df, $P = 0.005$) with pulse duration significant ($\chi^2 = 4.27$, 1 df, $P = 0.04$) but not pulse frequency ($\chi^2 = 3.48$, 1 df, $P = 0.06$).

Changes in repel rate increased with increasing voltage and were similar between day and night (Figure 4). As the videotaped observation area differed between day and night tests, we did not compare results directly. However, night tests produced similar odds ratios for voltage when compared with the day tests (Table 1). Generally, the repel rate increased with increasing voltage; this trend was more pronounced and became significant at $P = 0.05$ during night observations. Round goby were 10 times more active at night than during the day in the control. Activity, as demonstrated by the number of attempts to cross the barrier, was significantly reduced once the barrier was activated (ANOVA, $F_{2,9} = 9.24$, $P = 0.01$).

As expected, the electrical current field was measurably different when 70 and 100 V were applied to the barrier. When 70 V were applied to the three electrodes, the measured voltage in the test tank peaked at 2.6 V/cm near the middle electrode (Figure 5A). When 100 V were applied, the measured voltage again peaked near the middle electrode at 4.9 V/cm, almost twice the measured voltage when 70 V were applied (Figure 5B).

Field

Control tests were conducted to determine whether marked round goby would move quickly across the barrier if no electricity was applied. Marked round goby were released above the barri-

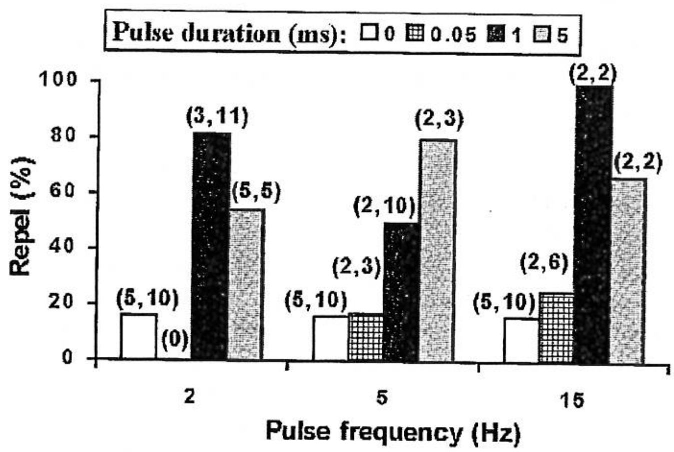

Figure 3. The percentage of round goby that were repelled from crossing the electrical barrier under laboratory conditions with 70-V pulsed direct current and different pulse frequencies (Hz) and pulse durations (ms). The number of tests and the average number of attempts per test are shown respectively in parentheses. The control data (0-ms-pulse duration or 0 V) are shown at each pulse frequency for comparison.

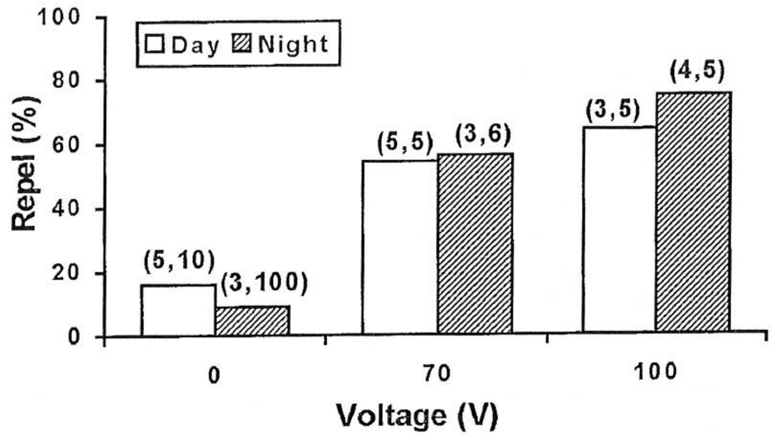

Figure 4. The percentage of round goby that were repelled from crossing the electrical barrier under laboratory conditions at different voltages of pulsed direct current with a 2-Hz-pulse frequency and at 5-ms-pulse duration during day and night observations. The number of tests and the average number of attempts per test are respectively shown in parentheses.

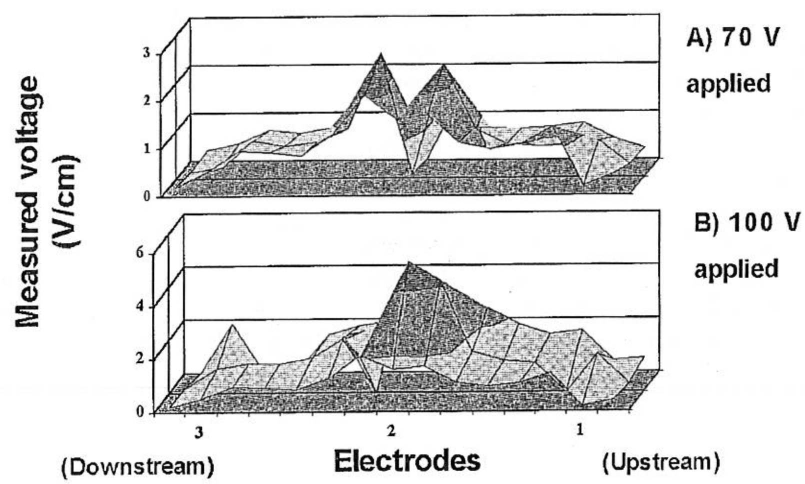

Figure 5. Voltage (V/cm) measured over the three electrodes in the laboratory test pool when (A) 70 V and (B) 100 V were applied to the electrodes. Placement of electrodes 1–3 is shown in Figure 1.

er on 20 August 1998. Observers stationed across the stream width at the barrier observed 5 of 18 round goby crossing the barrier within 20 min of release. After 1 d, four marked round goby were recaptured from seining below the barrier. After conducting the control study, further work was spent on better securing block nets and developing effective recovery methods.

The field electrical barrier was tested at two electrical settings (differing in electrical pulse duration) with three tests at each setting (Table 2). The electrical barrier at the stream site produced a measurable electrical field (Figure 6). As in the laboratory, when 100 V were applied to the electrodes, the electrical field measured peaked at 4.9 V/cm at the center of the barrier. Changes in pulse durations from 5 to 3 ms did not alter the field appreciably.

In the field tests, most round goby were recovered within 1 d of release (Table 2). Only live round goby were found above the barrier. Although not quantified during recovery efforts, round goby were often concentrated in deep areas (or holes) and in vegetation upstream of the barrier. Both live and dead round goby were found on the barrier, but the live round goby were stunned and easily recovered by hand nets. In the first set of tests (trial 1,

Table 2. Location (above, on, or below the electrical barrier) of round goby recovered after each 24-h test under the electrical parameters noted above each set of experiments. Numbers of round goby alive or dead were recorded in each location. In addition, the number recovered after 1 day and the total recovered throughout the study for each test (25 round goby released for each test) are given.

	Location of recovered round gobies			Round gobies recovered
Test	Above barrier	On barrier	Below barrier	Day 1/total
		100 V, 5 ms, 2 Hz		
1	2 live	0 live, 18 dead	2 dead	19/22
2	14 live	3 live, 5 dead	0 dead	17/22
3	18 live	2 live, 4 dead	0 dead	18/24
		100 V, 3 ms, 2 Hz		
4	12 live	3 live, 5 dead	1 live, 0 dead	19/21
5	7 live	4 live, 6 dead	2 live, 5 dead	23/24
6	8 live	0 live, 3 dead	0 live, 3 dead	14/14

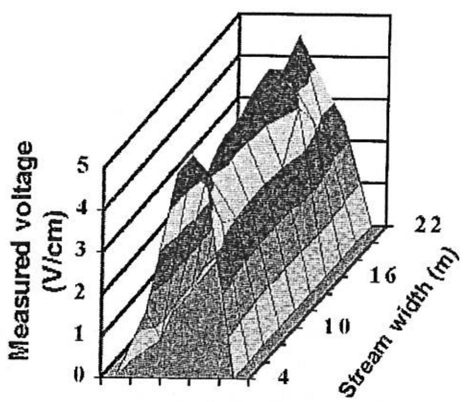

Figure 6. Voltage (V/cm) measured over the electrical barrier at the stream test site when 100 V has applied to the four electrodes.

three replicates), the only marked round goby found below the barrier (100 V, 5 ms pulse duration, and 2 Hz pulse frequency) were dead. At reduced pulse durations (100 V, 3 ms, 2 Hz) in the second set of tests (trial 2, three replicates), a few round goby (mean one/test) were found alive below the barrier, but were in poor condition and easily captured by hand nets.

Round goby tested averaged 95 mm TL (range: 60–120 mm). Sizes of round goby did not differ between those released and recaptured in trial 1 ($F_{1,141}$ = 0.23, P = 0.64) or trial 2 ($F_{1,131}$ = 0.04, P = 0.84). Among those recaptured, sizes of round goby did not differ between those found live or dead in trial 1 ($F_{1,66}$ = 0.43, P = 0.52) or in trial 2 ($F_{1,56}$ = 0.79, P = 0.38). Sizes also did not differ in location of those found above, on, or below the barrier in trial 1 ($F_{2,65}$ = 0.01, P = 0.99) or in trial 2 ($F_{2,55}$ = 0.78, P = 0.46).

A few small resident, unmarked round goby were captured in the stream during tests while seining: the mean size of two round goby per test (range: 0–4) averaged 50 mm TL (SD = 9.4 mm). Other stream fishes collected during seining at the field site (within the block nets) included: bowfin *Amia calva*, common carp *Cyprinus carpio*, golden shiner *Notemigonus crysoleucas*, common shiner *Luxilis cornutus*, spottail shiner *Notropis hudsonius*, spotfin shiner *Cyprinella spilopterus*, bluntnose minnow *Pimephales notatus*, madtoms *Noturus* spp., largemouth bass *Micropterus salmoides*, bluegill *Lepomis macrochirus*, pumpkinseed *Lepomis gibbosus*, and darters *Etheostoma* spp. Crayfish, frogs, snapping turtles, and water snakes were also plentiful at the field site, but not identified to species. A few nontarget species were found dead on the barrier during the six trials; these included one large snapping turtle; one large bullfrog, two bluntnose minnows; one common carp (about 80 cm TL), one resident round goby (unmarked), and several bluegills and pumpkinseeds.

Discussion

Round goby, once introduced into the Great Lakes, have dispersed through three main mechanisms: ballast-water transfer, bait-bucket dumping, or natural swimming movement and dispersal. This laboratory and field study addresses unaided migratory movements and was conducted to determine the feasibility of using electrical barriers to deter movement of round goby through canal systems. The barrier was about 80% effective in repelling round goby during short-term tests in the laboratory. Differences in day-time and nocturnal activity of round goby did not change effectiveness of the barrier. However, the scale-up study in a small river was almost 100% effective in deterring round goby movement downstream. This difference in effectiveness could be the result of several factors. A primary difference in methods was that round goby in laboratory studies were subjected to the electrical field for only 2 h, and fish were removed from the electrical field if stunned. However, round goby in the field study that moved within the electrical field tended to dive and remained near or under electrodes until they died. Anodic attraction is one of the possible fish responses to electrical fields (Kolz and Reynolds 1989). About 12% of the round goby in the laboratory study were stunned while 20–40% of the round goby were stunned or killed on the barrier in the field study. The low flow (0.3–0.5 cm/s) at the field site carried few dead or stunned round goby through the barrier. On a larger scale, the barrier design in the Illinois Waterway System includes the use of railroad rails for large electrodes. Round goby that are stunned near these rails could remain trapped against the protruding upstream side even under regular flow conditions until killed.

Other changes in scale between the laboratory and field studies could account for further differences in round goby responses. The electrical barrier in laboratory studies had a shorter crossing distance (<1 m) and round goby were concentrated in a narrow channel (0.6 m wide). Round goby are an aggressive fish (Dubs and Corkum 1996). In one instance, we observed a round goby forcing another through the barrier. Even though this aggression was rarely observed directly in the laboratory, concentrating round goby in a narrow channel could enhance aggressive interactions and possibly increase the number of passages through the barrier. In the field, the electrical barrier was over a 6-m stretch downstream and covered a 20-m stream width. Round goby could swim through the relatively short length of electrical current in the laboratory, but appeared unable to complete the passage in the field.

In each group of round goby, some individuals appeared determined to cross the barrier. In the laboratory about 12% of those attempting to cross the barrier, actually made it through; in the field they were stunned or died. Other round goby appeared to learn from encountering the barrier. In the laboratory, the number of attempts decreased after experience with the barrier. The number of attempts decreased significantly from controls under both day and night conditions by activating the barrier. Learning has been demonstrated in other fish behaviors such as foraging (Savino and Hudson 1995; Savino et al. 1993). Nevertheless, attempts to cross the barrier continued to be made in both the laboratory and field. In practical applications, it is extremely important that the barrier remain active. Immediately after an electrical barrier was shut down, sea lampreys moved through the stream section (Swink 1999). Through constant exploration, Atlantic salmon *Salmo salar* determined in less than an hour that barriers were off in laboratory studies and moved across an electrical barrier (Stewart 1981).

Our electrical parameters varied from others used in the literature. Our peak electrical field intensities were somewhat higher (5 V/cm) than those used in another study (3.0 V/cm) to effectively block the movement of a variety of species (gizzard shad *Dorosoma cepedianum*, golden shiner, rainbow trout, brown trout *Salmo trutta*, and largemouth bass; Barwick and Miller 1996). Lowering the peak to 3 V/cm in this laboratory study produced a noticeable decrease in effectiveness. Duration of electrical pulse was also important in determining the effectiveness of the field in both this laboratory and the field study—longer pulse duration better deterred movement downstream. Swink (1999) also found that longer pulse durations provided a more effective barrier; pulse durations of 2 ms (10 Hz) completely blocked sea lamprey migration upstream whereas 1 ms pulse duration (10 Hz) allowed 1 out of 900 marked sea lampreys to pass the barrier. In water with lower conductivity (40 μS/cm), chinook salmon were guided with 168 V, 3.7 ms duration, and 120 Hz (Palmisano and Burger 1988).

Native fish species were affected little by the barrier. Either they were repelled or they moved through the barrier. A few larger organisms died on the barrier; larger organisms are more affected by electricity as they conduct more current (Monan and Engstrom 1963; Klima 1972). However, we also saw several common carp and bowfin pass upstream through the barrier. Behavioral and physiological studies have shown that fish in many situations are affected by electric shocking, but generally return to normal parameters within 24 h (Schreck et al.

1976; Sorensen 1994; Maxfield et al. 1971; Mesa and Schreck 1989). Rainbow trout survival, growth, and fecundity were not affected by shocking (1 V/cm, 40 ms, 8 Hz). Goldfish *Carassius auratus* and brook trout *Salvelinus fontinalis* did not alter spawning behavior 1 d after being electroshocked (Sorensen 1994). Feeding and aggression of cutthroat trout *Oncorhyncus clarki* initially decreased but returned to normal within a day of shocking (Mesa and Schreck 1989). Some fish have shown spinal injuries, e.g. rainbow trout captured by electrofishing (260 V, 60 Hz; Sharber and Carothers 1988). Further tests will be needed to determine effects on native species. However, recall that what may be native to one watershed may not be native to the adjoining watershed. If the objective is to achieve complete blockage of fish passage in either direction along an artificial connection, electrical parameters may need to be enhanced or alternative barriers may need to be put in place.

Life stage is another important factor to consider in determining the effectiveness of electric barriers in deterring downstream movement. We worked with fish 60–120 mm in length, generally adults. Smaller life stages have not been studied. Godfrey (1957) showed that shocking with high voltages (550 V) caused high mortality in green eggs of Atlantic salmon and brook trout but not in eyed eggs; alevins were killed by prolonged shocking. Survival and growth of age-0 rainbow trout were not affected (Maxfield et al. 1971). Generally smaller fish are impacted less, since they conduct less electrical current (Monan and Engstrom 1963; Klima 1972). Round goby eggs are adhesive and are attached to the underside of rock or other surfaces (Corkum et al. 1998); they should not flow down river. However, larval or juvenile round goby could migrate. Recent studies suggest that young round goby migrate farther than adults (L. D. Corkum, University of Windsor, personal communication). Therefore, barriers need to be developed and tested that are effective for fish of smaller size classes.

The barrier tested as part of this study should be considered the first phase in deterring fish movement through a canal. At the suggested location for the electrical barrier in the Illinois Waterway System, water velocities are generally less than 0.3 m/s, but can reach 1.5 m/s (Keppner and Theriot 1997). The planned electrical barrier is designed to extend throughout the water column, but under conditions of high-water velocities, stunned round goby might wash downstream. The electrical barrier would prove more effective in smaller canals in areas with little or no flow.

Barriers are most effective for stopping upstream movement, as with common carp and bigmouth buffalo *Ictiobus cyprinellus* (Verrill and Berry 1995) or sea lamprey (Swink 1999). Guiding fish around obstacles, inlets, or channels and into preferred areas (mainstream, fish ladders) has had mixed success (Palmisano and Burger 1988; Kynard and O'Leary 1993; Barwick and Miller 1996). Barriers have not been shown to be entirely successful in preventing downstream movement of fishes (Kynard and O'Leary 1993; Swink 1999). Other types or additional barriers will be essential if complete blockage of fish movement through the area is desired. Considerations include acoustic bubble barriers or hydrojets. Bubble barriers proved somewhat effective in confining roundfish but not flatfish over several-hour field tests (Stewart 1981). Infrasound (10 Hz) produced avoidance behavior in chinook salmon and rainbow trout (Knudsen et al. 1997). In addition, the Illinois Waterway System demonstration project calls for a second electrical barrier. The strategy is that if round goby pass through this first barrier, they may be temporarily stopped by the second. Our studies suggest that round goby appear to learn from their first experience with an electrical barrier that results in a reduction of further downstream attempts. However, this learning does not prove 100% effective in deterring further attempts. Hence any round goby caught between two electrical barriers, should be trapped and removed from this area. In our study, round goby concentrated above the barrier in deep holes and macrophytes. This fish behavior may be able to be used as an advantage at bigger installations to concentrate round goby and other target fish and remove them by some other means (predators, chemicals, electricity). Ideally, a flat featureless area could be installed in front of the barrier with areas of structure, holes, or trenches to concentrate fishes so that some type of removal process is more efficient and effective.

In summary, the choice and verification of the efficacy of an electrical barrier was an important first phase in the demonstration barrier project. The electrical barrier proved effective in deterring adult round goby movement across a section of a small stream. However, effects of scale need to be considered in canals where the water is deeper and the flow is faster. Other studies are planned to determine effects of the electrical barrier on younger life stages of round goby and on native fauna. To form a more effective barrier and provide backup, the electrical barrier could be used in tandem with other (acoustic bubble) barriers.

Acknowledgments

David Smith, President, and Jeff Smith, General Manager, of Smith-Root, Inc. (14014 NE Salmon Creek Avenue, Vancouver, Washington 98686 USA) provided the electrical barrier equipment and logistical support. Margret and Hugh Mead graciously provided access and use of their streamside property for this study. Numerous volunteers aided in collecting round gobies and in helping carry out laboratory and field studies. We especially thank Stephanie Carman and Julie Ryan for their assistance in setting up the barrier nets, John French and Margi Chriscinski for their constant aid, and S. Jerrine Nichols for supplying zebra mussels for food. Rainbow trout eggs were provided by Wes Orr (Ennis National Fish Hatchery, Ennis, Montana 59729). This study was partially funded by the U.S. Army Corps of Engineers with Military Interdepartmental Purchase Request W81G6681317119. Dr. Philip Moy (Wisconsin Sea Grant, Manitowoc, Wisconsin), formerly of the USACE, instigated the study and provided constant feedback. This is contribution 1132 of the Great Lakes Science Center and contribution 617 of the Center for Great Lakes and Aquatic Sciences, University of Michigan.

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Can Hydraulic Barriers Stop the Spread of the Round Goby?

by Jan Jeffrey Hoover, S. Reid Adams, and K. Jack Killgore

BACKGROUND: The round goby, *Neogobius melanostomus*, a native of Eurasia, is spreading throughout the waters of North America (Figure 1). Native to the Black Sea and Caspian Sea systems, the round goby appeared in the St.Clair River, ONT-MI in 1990, and subsequently in the Great Lakes during 1993-1996 (Charlebois et al. 1997). Particular concern exists for the population in southern Lake Michigan and the Calumet River, which is spreading west via the Cal-Sag Channel towards the Des Plaines River (Moy 1997). Penetration by the round goby into the Mississippi River system, or any large river system, would allow virtually unlimited spread throughout large geographic areas. Its high rate of dispersal (e.g., all five Great Lakes in only 5 years) is particular cause for concern (Jude 1997).

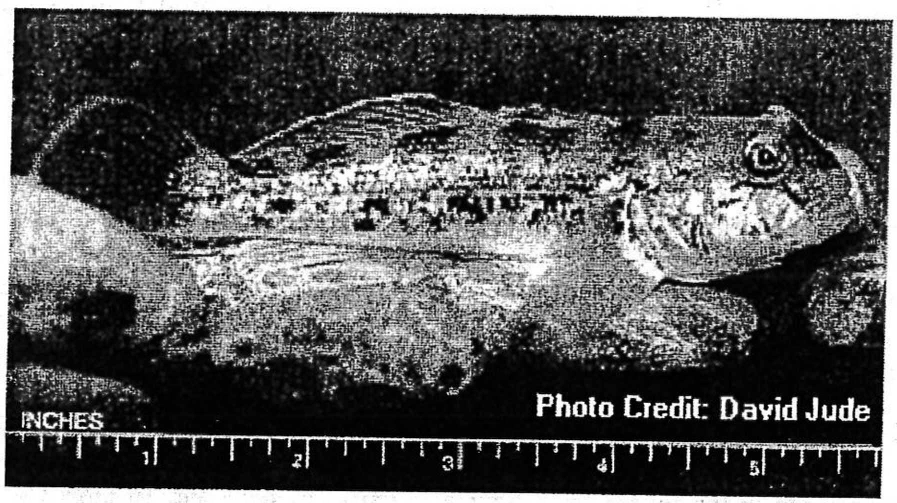

Figure 1. Round goby (*Neogobius melanostomus*). Photograph provided by David Jude, School of Natural Resources and the Environment, University of Michigan

This benthic species, although small, is highly aggressive toward native fishes, especially the mottled sculpin (*Cottus bairdi*), which is unable to effectively defend the cavities it normally inhabits from gobies (Dubs and Corkum 1996). The round goby is also aggressive towards larger, pelagic species such as rock bass (*Ambloplites rupestris*) and smallmouth bass (*Micropterus dolomieui*) (Wickett and Corkum 1998), as well as smaller, benthic species like darters, *Etheostoma* spp. (Jude 1997). Containment of the round goby has been identified as a priority by several agencies, including the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service. The round goby could be contained by use of ichthyocides, electricity, or by hydraulics. The last of these is environmentally benign and safe, but efficacy is unknown.

PURPOSE: To evaluate potential for hydraulic containment of round gobies, three questions were addressed in a series of laboratory experiments:

- What are the station-holding capabilities of round gobies?
- How is station-holding endurance influenced by substrate?
- Are goby movements effectively contained by hydraulic barriers?

Round gobies were tested in a series of laboratory experiments to determine whether hydraulic containment of populations was possible. Station-holding endurance models, critical station-holding velocity tests, and a small, low-velocity barrier in a simulated stream all indicated that containment was feasible, but that barrier specifications would have to be adjusted to local conditions (bottom topography, substrate size, water temperature).

METHODS: Specimens were obtained by angling during the summer of 1998 and sent by overnight delivery to the Waterways Experiment Station. They were maintained in 300-L Living Stream fiberglass aquaria (model 510, Frigid Units, Toledeo, OH) filled with dechlorinated tap water. Tanks provided slow (< 10 cm/s) rectilinear flow and constant water temperature. Tank bottoms were left bare but pieces of PVC pipe were used to provide bottom cover. Gobies were fed twice daily: frozen bloodworms (Chironomidae), dry salmon pellets (Silver Cup Salmon Crumbles, Nelson and Sons, Inc., Murray, UT). Light-dark cycle approximated natural conditions.

Predictive Endurance models – Station-holding endurance was evaluated in a propeller-driven, 100-L Blazka swim tunnel (Beamish 1978) using protocol developed for another benthic fish, juvenile pallid sturgeon (Adams et al. 1999). Tunnel had a working section 39 cm long, 15 cm diameter, with two sets of flow filters to promote microturbulent, rectilinear flow. Tunnel velocities were measured and calibrated to specific rheostat settings on the electric motor using a Marsh-McBirney flow meter.

Thirty-six hours prior to testing, gobies were isolated from the population and not fed to achieve post-absorptive state. At time of testing, a fish was transported to the swim tunnel in a water-filled PVC cylinder, habituated in the tunnel for 1 hour at 5 cm/s (30 min) and 10 cm/s (30 min). Following habituation, water speed was increased rapidly (2-4 sec) to test velocity. The fish was observed for station holding, and time to fatigue was recorded. If a goby was able to maintain position at a particular speed for 200 min (or more), then that speed was considered to represent sustained station-holding. If the fish was unable to maintain a particular speed indefinitely (i.e., it fatigued), the speed represented prolonged (0.5 to 200 min) or burst station holding (< 0.5 min). Fish were allowed to maintain station by swimming or by substrate appression, and no attempt was made to alter behavior. Fish were considered fatigued when they could no longer swim or maintain position without bracing against or becoming impinged upon the downstream screen of the working section of the tunnel after which they would not respond to mechanical stimulation (gentle prodding). Test velocities ranged from 15-75 cm/s.

Gobies were tested only once. After testing, total length (TL) of the fish (to the nearest 1 mm) and weight (to the nearest 0.01 g) were recorded. Gender was recorded only for those fish in which the shape of the urogenital papillae could be definitively categorized as male or female (based on

Charlebois et al. (1996)). A small series of fish (N = 39) was tested at 20 °C, another larger series (N = 111) at 17 °C.

The predictive relationship between water velocity and fish size (independent variables) and endurance (dependent variable) was quantified using linear and polynomial regression techniques (Statistical Analysis Systems, Carey, NC). The model that accounted for the highest degree of data set variance (r^2) was chosen. Swimming trials in which fish did not fatigue (i.e., sustained swimming) were excluded from models. Length-weight relationships were also analyzed using $\log_{10}$ conversions of data and linear regression.

Influence of substrate roughness - Critical swimming/station-holding speed was determined over various substrates in the Blazka swim tunnel. The tunnel was modified with interchangeable horizontal Plexiglas inserts that rested on the bottom of the working section of the tunnel. Inserts were bare, covered with a layer of sand, or covered with a layer of gravel (5-10 mm), simulating substrates that are smooth (e.g., bedrock), fine, or coarse. Individual fish were introduced into the tunnel, habituated, and subjected to increasing water velocity (at 5 cm/s increments) every 10 minutes until fatigued. Time at the fatigue velocity was recorded.

Critical station-holding speed was calculated according to Brett (1964):

$$U_{crit} = U_1 + (T_1 / T_2 \times U_2)$$

in which U_{crit} is the 10-min critical station-holding speed, U_1 is the highest water velocity maintained for the prescribed time period, T_1 is the duration of swimming at the fatigue velocity, T_2 is the prescribed period of swimming (or 10 min), and U_2 is the velocity increment (5 cm/s). Fish were tested once. Seven fish were tested for each substrate insert. Differences among substrates were evaluated using MANOVA and the Tukey HSD test (Statistica StatSoft Inc., Tulsa, OK).

Physical model of a hydraulic barrier - Short-term containment of round gobies was demonstrated in a laboratory stream with a simulated "containment field." This laboratory stream is an elliptical channel, shaped like a racetrack and made of aquamarine fiberglass (Model SM, Frigid Units, Toledo Ohio). It is 5.5 m long. Channel is 31 cm wide and water is 26.5 cm deep. Total water volume is 1000 L. Water is drawn continuously from the surface. It is piped into a filter-aerator consisting of a 20-L bucket with a porous bottom, containing floss, carbon, and foam. Filtered water collects in a reservoir with a water volume of 236 L and containing a Little Giant submersible pump (Model 3E-34N, Oklahoma City, OK), which returns water to the channel. Water enters the channel from the reservoir through a PVC pipe generating the hydraulic barrier. The inflow pipe is 30 cm long, perpendicular to the long axis of the channel, and is suspended 4 cm above the channel bottom. This position allows for near-uniform flow throughout the channel and in the event of interrupted power, prevents the channel from draining completely. Water velocity is 29.5 cm/s 1 m from the barrier, 13.5 cm/s 2 m from the barrier, and 9.0 cm/s 3 m from the barrier. A screen placed 3 m "downstream" from the barrier defines the lower limit of the containment field. Six trials were conducted: three controls using non-flowing water and three treatments using flowing water. In each trial, nine gobies were released within the containment field. The number of individuals crossing the barrier was determined after 24 hr.

RESULTS

Size of gobies and behavior - Gobies tested ranged in size from 43 – 154 mm TL (N = 150). Individuals identifiable as males were 72-154 mm TL (N = 63); females were 75-136 mm TL (N = 34). Length-weight relationship for all fish was:

$$\text{Log}_{10}\text{ Weight} = 3.13\ (\text{Log}_{10}\text{ Length}) - 5.13,\ r^2 = 0.98,\ p < 0.0001$$

This relationship was not substantially different than models generated for males,

$$\text{Log}_{10}\text{ Weight} = 3.04\ (\text{Log}_{10}\text{ Length}) - 4.94,\ r^2 = 0.97,\ p < 0.0001$$

or for females,

$$\text{Log}_{10}\text{ Weight} = 2.83\ (\text{Log}_{10}\text{ Length}) - 4.53,\ r^2 = 0.96,\ p < 0.0001$$

Gobies in all three experiments spent very little time (< 20 percent) swimming in the water column, or skimming along the surface of the bottom. Instead, they hunkered close to the bottom, appresssing themselves to it, as they turned about or darted forward and backward.

Predictive endurance models - Stepwise multiple regression analyses indicated that for both water temperatures, endurance was negatively correlated with water velocity and positively correlated with length of fish. There were notable differences in swimming speeds between temperatures. At 17 °C, the relationship was:

$$\text{Log}_{10}\text{ Endurance} = -0.027\ (\text{Velocity}) + 0.007\ (\text{Length}) + 0.516,\ r^2 = 0.62,\ p < 0.0001$$

At 20 °C, the relationship was:

$$\text{Log}_{10}\text{ Endurance} = -0.028\ (\text{Velocity}) + 0.005\ (\text{Length}) + 0.940,\ r^2 = 0.67,\ p < 0.0001$$

At both water temperatures, water velocity was the primary variable accounting for endurance (partial $r^2 > 0.55$). The influence of fish size in the multiple regression models, although statistically significant ($p < 0.09$), was relatively low (partial $r^2 < 0.07$). To minimize the influence of fish size on endurance data, however, data were analyzed separately for small fish (< 90 mm TL) and large fish (> 90 mm TL).

At 17 °C, small gobies exhibited sustained station holding at 15 cm/s, prolonged station holding (0.5-44 min) at 20-50 cm/s, and burst station-holding at 55-75 cm/s (Figure 2). Large gobies exhibited sustained swimming at 20 cm/s, prolonged swimming (0.5-72 min) at 20-50 cm/s, and mostly burst station holding at 55-75 cm/s. Although endurance values of the two size groups overlapped at most water velocities, larger fish typically had greater endurance than smaller fish. At 20 °C, sustained station holding was not observed (Figure 3). For small gobies, prolonged station holding (0.5-61 min) was observed at 15-55 cm/s, burst at 60 cm/s. Only 12 large fish were run at 20 °C and none of these were tested at water velocities < 40 cm/s. Data suggest that larger fish had greater endurance than the smaller fish over this range of water velocities. Overall, station-holding endurance at lower water velocities (< 30 cm/s) was higher at the cooler temperature; endurance at higher water velocities (> 30 cm/s) was higher at the warmer temperature. Definitive statements regarding differences in swimming performance at different water temperatures cannot be made at this time, since tests were discontinued at 20 °C due to apparent stress experienced by gobies at that temperature (based on aberrant behavior and post-test mortality). Because endurance decreased curvilinearly with increased water velocity, polynomial models were used to describe the relationship between the two variables (Table 1).

Influence of substrate roughness - Fish exhibited improved station-holding times with increased roughness of the substrate. Mean critical station-holding speeds (and standard deviations) were 20.7 (3.4), 42.4 (4.6), and 52.5 (2.0) cm/s on Plexiglas, sand, and gravel substrates respectively. Significant differences existed among the values (df = 2/18, $F = 147.96$, $p < 0.0001$). Each mean value was statistically different from each of the other values ($p < 0.0003$). Differences among values were not attributable to differences in size of fish among treatments. Mean sizes of fish ranged from 77.4-78.9.

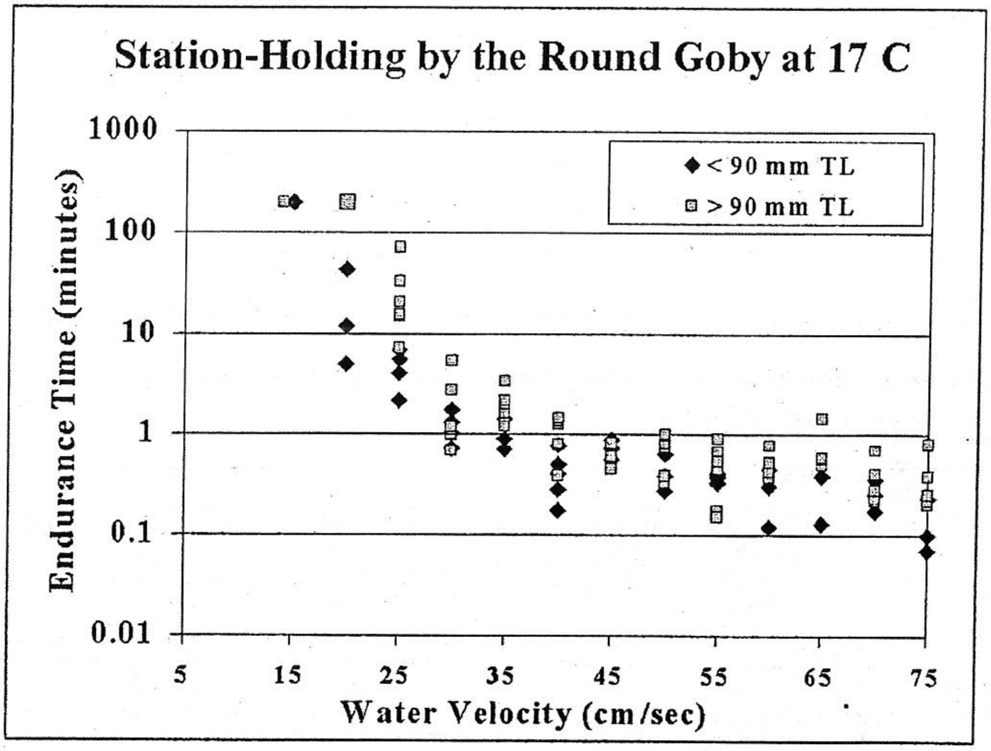

Figure 2. Station-holding by two size classes of round gobies in cool water

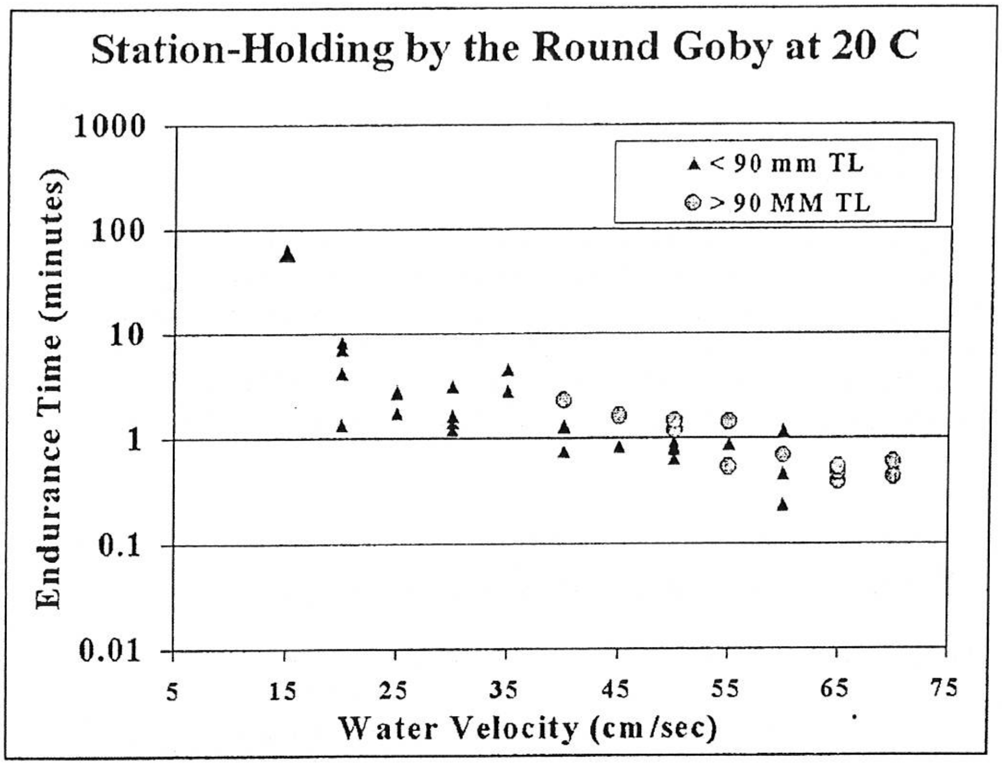

Figure 3. Station-holding by two size classes of round goby in warm water

Table 1
Polynomial Regression Models Relating Endurance Time of Round Goby (Minutes) to Water Velocity (in cm/s)[1]

Temperature °C	Size Class	Model	N	R^2	p
17	Small	Log_{10} Time = 0.0007 (Vel^2) - 0.0969 (Vel) + 2.5471	41	0.79	< 0.0001
17	Large	Log_{10} Time = 0.0009 (Vel^2) - 0.1156 (Vel) + 3.2207	63	0.67	< 0.0001
20	Small	Log_{10} Time = 0.0006 (Vel^2) - 0.0727 (Vel) + 1.9955	27	0.67	< 0.0001
20	Large	Log_{10} Time = 0.0004 (Vel^2) – 0.0676 (Vel) + 2.4848	12	0.82	0.0005

[1] Small fish were 65-88 mm TL; large fish were 91-154 mm TL. Round gobies were tested over a range of 15-75 cm/s with the exception of large fish run at 20 °C, for which data were obtained only at 40-70 cm/s.

Physical model of a hydraulic barrier - Gobies were contained by the small-scale physical model of a hydraulic barrier. During three trials, when the barrier was non-operational, gobies freely distributed throughout the experimental channel. During three trials, when the barrier was operational, all gobies were contained behind the barrier in two trials, despite frequent, prolonged approaches of the barrier. During the third trial, a goby crossed the barrier and had escaped the containment field.

DISCUSSION: Size of gobies was comparable to previous reports and is probably representative of the population in the Great Lakes Region. Size range was nearly identical to that reported for Calumet Harbor, approximately 60-145 mm TL, as was the similarity in weights of males and females (Charlebois et al. 1997).

Gobies are not powerful swimmers, maintaining station primarily by pressing their bodies to the substrate, and their ability to hold station is positively correlated with substrate roughness or size. A hydraulic barrier, to effectively contain round gobies, would not only have to provide sufficiently high water velocities over a sufficiently great distance to exceed their physiological endurance, but would also have to be located in a relatively straight-sided channel with smooth substrate so as to exceed their behavioral mechanisms for avoiding or withstanding flow. If such channels exist in local areas of concern, then the likelihood of containment seems promising. If such a channel does not exist, than hydraulic containment would have to rely on elevated water velocities (e.g., greater than 75 cm/s) or prolonged distances of moderate velocity generation.

ACKNOWLEDGMENTS: This project was funded by the U.S. Army Engineer Chicago District. Bradley Lewis assisted in the laboratory. Phil Moy arranged for delivery of fish. Permission to publish this document was granted by the Chief of Engineers.

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> Hoover, J. J., Adams, S. R., and Killgore, K. J. (2003). "Can hydraulic barriers stop the spread of the round goby?" *ANSRP Technical Notes Collection* (TN ANSRP-03-1), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/ansrp*

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Journal of Great Lakes Research 33(2):295-302. 2007
https://doi.org/10.3394/0380-1330(2007)33[295:DVMORG]2.0.CO;2

Diel Vertical Migration of Round Goby Larvae in the Great Lakes

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and

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Received: January 19, 2005; **Accepted:** January 28, 2007

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ABSTRACT

One hypothesis for the transcontinental and intra-Great Lakes basin transfer of round gobies (*Neogobius melanostomus*) has been that round gobies were pumped into the ballast water of ships. During June 2005 in Lake Erie, we obtained evidence of a vertical migration of round goby larvae, when we collected 167 round goby larvae in surface ichthyoplankton net tows at night and zero during day. These results complemented similar findings from the Muskegon River estuary of Lake Michigan during 2003 and 2004, documenting diel vertical migration for the first time in larval round gobies. We suggest vertical migration behavior may have allowed larval round gobies to be transported to and within the Great Lakes via ballast water and dispersed in the Great Lakes via advection of 6.5–8.5-mm long larvae at the surface. Based on our results, if ballast water was only taken on near the surface during daylight hours from May through September when larval round gobies were present, it would have mitigated the spread of round gobies throughout the Great Lakes.

Keywords: Round goby, ballast water, larval fish

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