DRAFT
ADULT ROUND GOBY ELECTRICAL FIELD THRESHOLDS AND SWIMMING SPEEDS

MENASHA LOCK

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Fox River Navigation System Authority

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ACRONYMS

A

AIC	Akaike Information Criteria
AUC	Area Under the Receiver Operating Curve (AUC)

C

cm	Centimeter
CoxPH	Cox Proportional Hazards regression model
C_w	Ambient water conductivity

D

dAIC	Difference between current model and best AIC score
df	Degrees of freedom
DNR	Wisconsin Department of Natural Resources

E

E	Energy density
ETS	ETS Electrofishing Systems, LLC

F

F	Frailty
FRNSA	Fox River Navigation System Authority

G

GoF	Goodness of Fit
GLEC	Great Lakes Environmental Center, Inc.

H

Hz	Hertz

L

L	Round Goby length in cm

M

$\mu J/cm^3$	Units of energy density
µS/cm	Units of conductivity
$\mu W/cm^3$	Units of power density
mm	Millimeter
ms	Millisecond

P

p	Probability of independence (Chi-Square Test)
PDC	Pulsed Direct Current
PW	Pulse width
pps	Pulses per second

R

RMS	Root mean square

T

T	Temperature in degrees Celsius

V

v	Velocity
V/cm	Voltage gradient

1.0 INTRODUCTION

The Fox River Navigation System Authority (FRNSA) wishes to reopen Menasha Lock after the construction of an electric field fish barrier. Operating the lock would allow boaters to travel between Little Lake Butte Des Morts and Lake Winnebago (Figure 1-1) for the first time since the lock was closed in 2015. The lock closure was requested by Wisconsin Department of Natural Resources (DNR) to prevent range expansion of the invasive Round Goby (*Neogobius melanostomus*) into Lake Winnebago, where they could out-compete native species for resources and habitat and interfere with the spawning success of the area's important sport fisheries (Kornis et al. 2012). Round Goby were first encountered in Great Lakes system in 1990 in the St. Clair River (Kornis et al. 2012), since then they have spread to Lake Michigan, Green Bay, and the Fox River (Figure 1-1). Round Goby spread via stratified dispersal (Kornis et al. 2012), up to 4.9 km/year upstream (Brownscombe et al. 2012). It is hypothesized that the operation of Menasha Lock and a graduated field electric fish barrier will be enough to impede Round Goby from migrating into Lake Winnebago through the lock. Upon review of the permit application for the electric barrier in 2019, DNR presented FRNSA with several questions about how Round Goby will react to electric barriers and whether or not velocities created during operations of the locks is enough to fatigue the fish and stop their range expansion into Lake Winnebago.

Graduated field electric fish barriers have been installed in the United States and Europe, where they present upstream migrants with higher voltage gradients as fish progress into the field, eventually causing immobilization and potentially downstream drift (O'Farrell et al. 2011) or settling of negatively buoyant fish. The application of electrical fields in water leads to taxis, immobilization, and possible trauma (Noatch & Suski, 2012). Great Lakes managers have successfully deployed electric fish barriers to stop the spread of invasive Asian carp, with the barrier installed at the Chicago Sanitary and Ship Canal up to 100% effective for this species at higher electrical operating parameters of 0.91 V/cm (Parker et al. 2015). However, some studies have shown that schools of juvenile Gizzard Shad (*Dorosoma cepedianum*) may pass through, and fish may become hydraulically entrained and carried in barge bow wakes (Davis et al. 2016). No electric barrier has been installed with the expressed intent of stopping the spread of Round Goby; however, experimental data suggests such a barrier is effective (Savino et al. 2001).

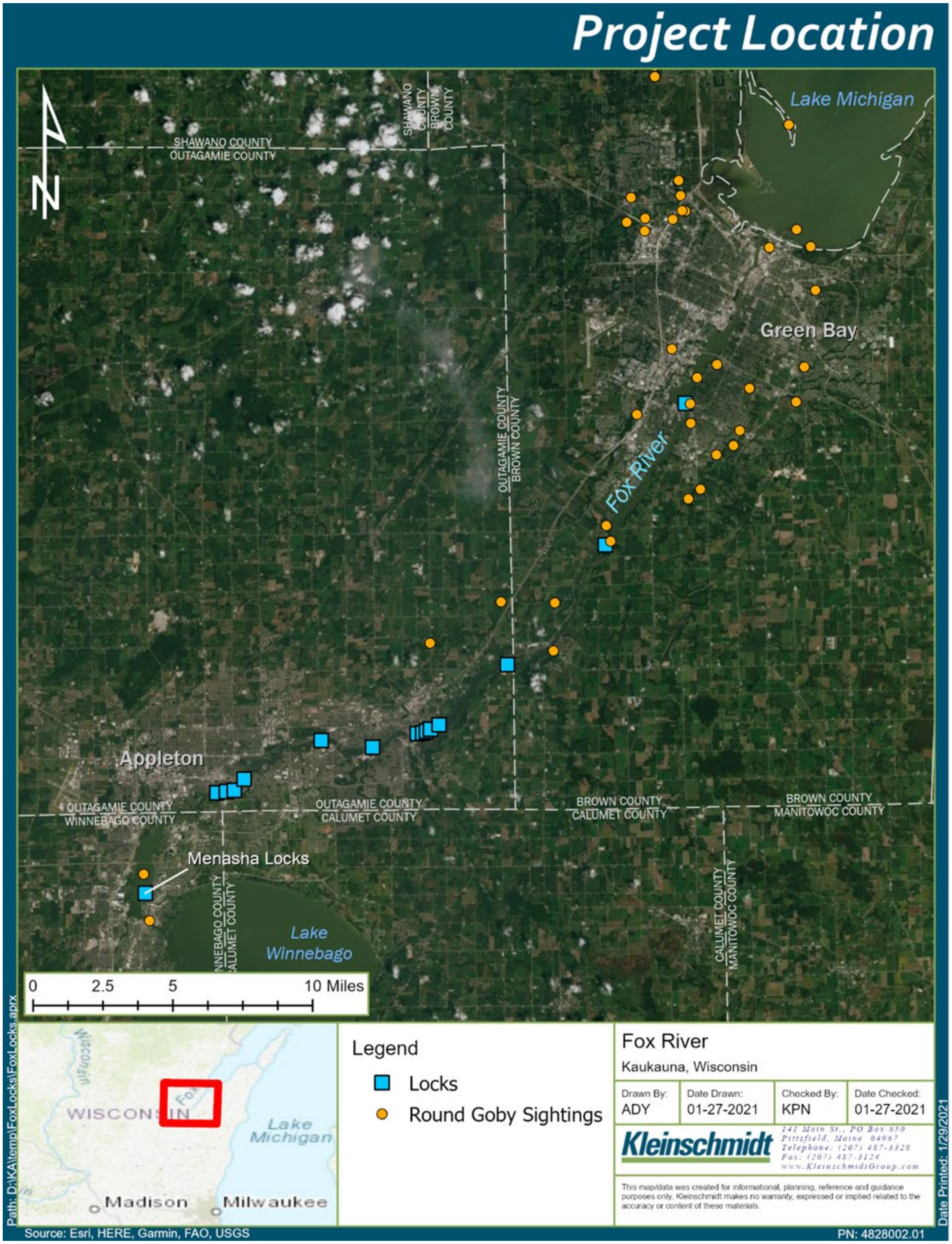

Figure 1-1 Project Location Map Showing the Location of Menasha Locks on the Fox River in Relation to Other Locks and Known Round Goby Sightings

Aside from the potential electrical barrier, normal operation of the Menasha Lock is estimated to produce water velocities in the area downstream of the lock up to about 30 cm/s. In 2003, Hoover, Adams, and Killgore studied the station-holding capabilties and endurance rates of gobies, and whether or not goby movements could be contained by hydraulic barriers. They found that gobies are not powerful swimmers and maintain station by pressing themselves against substrate, and conclude that a hydraulic barrier would have to provide sufficiently high water velocities (> 75 cm/s) over a sufficiently great distance and be located in a relative straight-sided channel with smooth substrate so as to "exceed their behavioral mechanisms for avoiding and withstanding flow" (Hoover et al. 2003). In recent work, Tierney et al. (2011) concluded that flow rates would need to be > 125 cm/s to prevent upstream movement and free of refuge areas in which to recover. Clearly, high water velocities over smooth substrate without velocity refuge is required. Coincidentally, electric barriers are designed to be robust, highly engineered, smooth structures, and coupled with regular maintenance as part of normal lock operations that would minimize the accumulation of of material that can act as a velocity shelter.

FRNSA will assess the probability that a fish will elicit a response (incapacitation) to an electric dose with logistic regression. Logistic regression has been used to assess electroshock-induced mortality response of Cape Fear shiner (*Notropis mekistocholas*), an endemic species to Cape Fear, North Carolina, USA (Holliman et al. 2003). Rather than mortality, FRNSA's desired electro-shock induced response for Round Goby is incapacitation. Regardless, the modeling strategy is the same, with predictive variables of electroshock dose, temperature, and total length. Castro-Santos (2004) used Cox Proportional Hazards regression (CoxPH) analysis to assess the time until fatigue of White Sucker (*Catostomus commersonii*) and Walleye (*Sander vitreus*) ascending a 23 m long flume along flows ranging from 1.5 to 4.5 m/s. FRNSA will assess the likelihood that Round Goby of specific size will become fatigued as a function of water velocity for fish held in a swim speed chamber with CoxPH.

2.0 METHODS

2.1 Study Team

The study team consisted of Kleinschmidt Associates (Project Lead), Great Lakes Environmental Center (GLEC), and Jan Dean, Ph.D. Kleinschmidt Associates managed the project, analyzed data, and provided written documentation. GLEC collected specimens, held them in their laboratory, and conducted the swimming speed studies. Dr. Dean conducted the electric dose experiments.

2.2 Capture and Handling

The study team made 35 trips into the field to collect Round Goby specimens for study. GLEC used light traps, baited minnow traps, and seine sampling to collect specimens. Once in the laboratory, GLEC kept fish in flow-through tanks (Figure 2-1) and were fed a diet of brine shrimp (genus *Artemia*), a commonly used food for captive fish. Mortalities were removed upon encounter and enumerated. In total, 551 fish were available for assessment.

Figure 2-1 Flow-Through Tank Set Up at GLEC

2.3 Electric Dose Experiments

The Round Goby lacks a swim bladder for buoyancy, so it typically remains on or near the bottom of the tank. The goby also has large pectoral fins and an unusual modification of its pelvic fins into a midline structure which can be used to adhere to substrate. Thus, the goby was not expected to elicit the same response typical of most fish in these types of studies; immobilization in most fish may be associated with a loss of equilibrium in which the fish rolls over on its side. To ensure a more accurate assessment of immobilization for Round Goby, each fish was repeatedly gently touched with a small diameter wooden (non-conductive) dowel rod to assess lack of response to tactile stimulation on its side, especially near its caudal peduncle. The dowel rod was also used to help align the fish body with the direction of the electrical current so that it experienced the maximum voltage drop through its body. Effort was made to point the fish head toward the anode plate electrode for consistency in threshold measurements. Immobilization thresholds generally are marginally lower when fish are facing the cathode, and that was demonstrated for the goby. Thus, the immobilization thresholds reported in this study are conservatively high to ensure an effective electrical barrier to goby movement if the fish are swimming upstream parallel with the electrical current of the barrier.

The minimum electric threshold required for immobilization of Round Goby was quantified with three separate components. The first included two experiments that provide information for choosing the pulsed direct current waveform (pulse frequency and duty cycle) for subsequent testing. Duty cycle is the percent of time the electric current is on. The second component determined if there was any effect of water temperature on Round Goby immobilization thresholds. The third component quantified the electric dose (power and time) required for Round Goby immobilization.

The tank used for all testing was a 10-gal glass aquarium of 24 x 48 cm filled to 20 cm depth. Plate electrodes of 11-gauge 304 stainless steel covered the flooded area of each tank end; distance between the plates was 48 cm (Figure 2-2). A uniform electrical field intensity in the test tank was verified with a voltage gradient probe attached to a Fluke 124B Scopemeter (oscilloscope). A uniform field means that the voltage gradient is the same anywhere inside the test tank; a uniform field provides the best condition to accurately assess fish immobilization thresholds. If the field is not uniform, fish could be exposed to a range of voltage and the actual mobilization threshold may be inaccurately estimated.

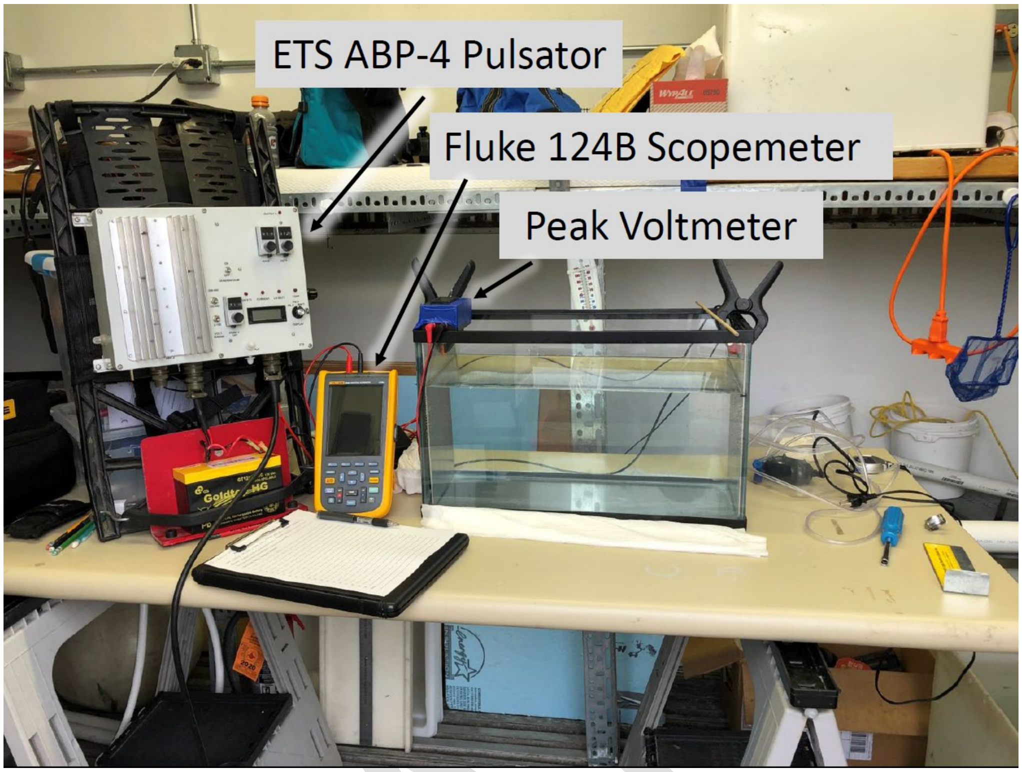

Figure 2-2 Electric Field Threshold Experimental Set Up

Component 1 included two experiments – a 5 ms pulse width (pulse duration) at different frequencies and the other with 3 ms pulse width. The aim of Component 1 was to examine the effectiveness and efficiency of each waveform. Maximum waveform effectiveness (in terms of energy use) was the waveform with the lowest peak power density (µW/cm3; microwatt per volume of water) that immobilized goby. Up to five fish were used for each frequency/pulse width treatment. Total length (1 mm) was measured and recorded for each fish, then a low level of voltage was applied to the plate electrodes and increased until the fish became immobilized (ramp-up method).

The threshold voltage gradient (V/cm) was calculated as threshold peak voltage divided by 48, the distance in cm between the plate electrodes. Peak voltage was read directly from the pulsator voltmeter and recorded. The pulsator was an ETS ABP-4 backpack electrofisher with independent and continuously adjustable controls for voltage, frequency and duty cycle. Pulsed direct current frequency and pulse width for each waveform were validated with the Fluke 124B Scopemeter. Duty cycle is the percent on time for a pulse; Duty Cycle (%) = Frequency (Hz) x Pulse Width (ms) / 10. Pulsed direct current (PDC) frequency is in pulses per second (pps), herein termed Hz.

Threshold voltage and ambient water conductivity (C_w) were combined to calculate peak power density (µW/cm^3) for evaluating waveform effectiveness. Ambient water conductivity and temperature were measured with a Hanna DiST 5 conductivity meter.

Peak Power Density = $(V/cm)^2 \times C_w$

Average power density (µW/cm^3) was used to evaluate waveform efficiency.

Average Power Density = Peak Power Density x Duty Cycle

The initial design for Component 1 included assessed 5, 10, 20 and 30 Hz treatments. The frequency treatments were randomly chosen using Excel's RANDBETWEEN function for the four frequencies coded as 1-4. Upon inspection of the results from Experiment 1 at 5 ms pulse width, additional trials were conducted at 15 and 25 Hz. For Experiment 2 at 3 ms pulse width, the frequencies tested were 10, 15, 20, 25 and 30 Hz. Also, after inspecting the 5 ms and 3 ms results, it was decided to include a treatment at 4 ms pulse width and 20 Hz. The 31 gobies used in Experiment 1 averaged 68.7 mm total length (range 57-82 mm). The 25 gobies used in Experiment 2 averaged 73.0 mm TL (range 59-86 mm).

Component 2 assessed the effect of temperature on immobilization, where 23 fish were kept at ambient water temperature (16.5°C) and another 23 were in a tank in which the water temperature was slowly increased (over ca. 5 days) to 24.7 C. Ambient conductivity increases at approximately 2 µS/cm per degree Celsius increase in water temperature. We eliminated this confounding factor by increasing the ambient conductivity by adding deionized water to the tank.

Fish in the temperature effect experiment were stocked into the test tank individually and exposed to a pre-assigned voltage for four seconds of 20 Hz, 5 ms pulsed direct current. If the fish were immobilized, the response was recorded as 1, else it was recorded as 0. Voltages for subsequent fish were adjusted up or down as needed to ensure a roughly equal mix of 1 and 0 responses. The results were analyzed via logistic regression which included voltage gradient, water temperature and fish total length as independent variables. Total length for the 46 fish averaged 69.2 mm (range 52-97 mm).

The quality of each model was assessed with the Hosmer-Lemeshow goodness of fit test. Significant models ($p < 0.05$) suggest the model meets goodness-of-fit criteria and adequately explains the variance. More than one model may meet goodness-of-fit criteria, and model selection was aided with use of Akaike Information Criteria (AIC) score and

Area Under the Receiver Operating Curve (AUC) score. The AIC score balances the predictive power of a model with its complexity. The best model is the most predictive with the least variables. Models are compared with the delta AIC or dAIC, which is simply the difference between the current model and best AIC score. The AUC score is a measure of the usefulness of the model. The higher the score, the better the sensitivity and specificity.

Component 3 was conducted to determine the electrical dose-response relationship for Round Goby. Four fish were used in a pre-trial assessment of dose thresholds to help choose the applied voltages for the actual trials. Results from these four fish were not included in the analysis of the dose-response data. The design of the dose-response experiment included shocking gobies at two voltages for 6, 12, 24 and 48 seconds. Based upon results from prior trials and from the four pre-trial fish, the first test voltage was 20 volts. Ambient conductivity and temperature for the dose-response trials were 252 µS/cm and 17.7 C. The order of exposure times was chosen randomly. Inspection of the 20-volt results was used to select 15 volts for the subsequent half of the experiment. Ten fish were individually exposed to each voltage-time combination using a 20 Hz, 5 ms pulsed direct current, and the results were recorded as 1 for immobilized and 0 for not immobilized.

Electrical dose included voltage gradient, duty cycle, ambient water conductivity (C_w) and exposure time (seconds) to calculate energy density in micro-Joules per cubic centimeter of water volume $\mu J/cm^3$.

Energy Density = $(V/cm)^2 \times C_w \times$ Duty Cycle x Exposure Time

The results were analyzed via logistic regression which included Energy Density and fish total length as independent variables. Total length for the 80 fish averaged 92.1 mm (range 54-152 mm). Models were assessed with the Hosmer-Lemeshow goodness of fit test, and model selection was aided with use of Akaike Information Criteria (AIC) score and Area Under the Receiver Operating Curve (AUC) score, where the best model has the lowest AIC and highest AUC.

In addition to the original study design was an experiment to estimate the effective conductivity of Round Goby. This estimate is important for adjusting immobilization voltage gradients and doses to other water conductivity. Effective conductivity, Cf, is a measure of fish conductivity based on the fish response (twitch, taxis, immobilization, etc.).) over a wide range of ambient water conductivity. The study was conducted in the same test tank using a 20 Hz, 5 ms (10% duty cycle) pulsed direct current waveform. Nominal water conductivities were 50, 80, 100, 120, 150, 180, 230, 300 and 400 µS/cm, all at approximately 16 C. Total length of the 46 fish averaged 74.5 mm (range 60-87 mm).

The last experiment, also in addition to the original study design, was designed to determine the minimum practical pulse width to which goby can respond. It is called the Chronaxie study. The 30 fish sample population averaged 70.8 mm (range 58-82 mm).

Reportedly, only eight novel (unshocked) fish remained after completing Components 1-3. Total gobies used for Components 1-3 were 194. Thus, the total number of fish available for the electrical portion of the Round Goby study was some 202 fish. The last two experiments, for C_f and Chronaxie, were conducted with 76 fish shocked prior but allowed to recover for a day or more; they appeared healthy and responsive. The total electrical study included trials of 270 gobies.

2.4 Swim Speed

GLEC constructed a swim speed chamber (Figure 2-3) and designed the study based on recommendations of Tierney 2011 and Tierney et al. 2011. To capture burst swimming or sprint ability, following acclimation, fish are placed in the rear of the polycarbonate swim speed chamber and the flow held for 160 seconds. Fish were motivated to swim by tapping the chamber or other mechanical or electrical means. The ability of the fish to maintain or advance position in the chamber is recorded, as is the duration of swimming. At the end of 160 seconds, velocity is increased, and after acclimation the fish is motivated to begin swimming. The trial stops when the fish can no longer hold its position or 160 seconds are met. The trials are repeated at water velocities of 0.0, 0.02, 0.13, 0.26, and 0.42 m/s for every fish.

Time-until-fatigue as a function of water velocity was assessed with Cox Proportional Hazards regression using the survival package in R. To control for repeated measurements on the same fish, the study team employed a frailty term. Frailty terms are a convenient way to introduce random effects into the model. A frailty is an unobserved random proportionality factor that modifies the hazard function of each individual. Some fish may be more prone to fatigue than others, they may be injured or sick. These factors are unobserved, but introduce variance into the data. Models were assessed with a likelihood ratio test and the assumption of constant hazards proportions was tested by examining the Schoenfeld Residuals. Model selection used AIC.

Figure 2-3 Swim Speed Chamber with Flow Meter Deployed

3.0 RESULTS AND DISCUSSION

3.1 Capture and Handling

GLEC made 35 trips into the field, with two sampling events cancelled due to gale force winds. In total, 831 fish were collected (Table 3-1), with the most fish collected via baited minnow traps. Some mortalities occurred during holding, with the largest single day mortality event of 100 fish occurred on September 29, 2020 (Table 3-1). At the end, 551 fish were available for analysis, with 125 allocated to the swim speed study and 426 allocated to the electric field threshold study.

Table 3-1 Results of the GLEC Collection and Rearing Efforts

Date	Light Traps	Baited Minnow Traps	Seine Hauls	Scuba	# Dead Removed	Comments
8/21/2020	0	0	40			
8/24/2020	0	0				
8/26/2020	0	0	53			
8/27/2020	0	0	31			
8/31/2020	0	13				
9/1/2020	0	0				
9/2/2020	0	0				
9/3/2020	0	2				
9/5/2020		6				
9/8/2020	0	12		2		
9/9/2020		20				
9/10/2020		9				
9/11/2020		35	67			
9/14/2020		22				
9/15/2020						Gale winds, no sampling
9/16/2020		4				
9/17/2020		14				
9/18/2020		25				
9/21/2020		26	46			
9/22/2020		30				
9/23/2020		19				
9/24/2020		5				
9/25/2020					12	
9/26/2020		6			50	
9/27/2020					40	
9/28/2020		8	0			
9/29/2020					100	Gale winds, no sampling
9/30/2020		39			25	
10/1/2020		23			29	
10/2/2020		119			8	
10/5/2020		8			10	
10/6/2020		43			0	
10/7/2020		55	6		0	
10/8/2020		37	4		4	
10/9/2020			2		2	

Source: GLEC

3.2 Electric Dose Response

Component 1 was designed to determine the pulsed direct current frequency and duty cycle for subsequent investigations of this overall study. A lower requirement of peak power density indicates a more effective waveform for immobilizing Round Goby. For a 5 ms pulse width (PW), the most effective frequency was 20 Hz. For a 3 ms PW, the threshold was somewhat lower at 30 Hz. A later addition of a 4 ms PW trial at 20 Hz indicated a peak power density threshold intermediate to those at 5 ms and 3 ms (Figure 3-1).

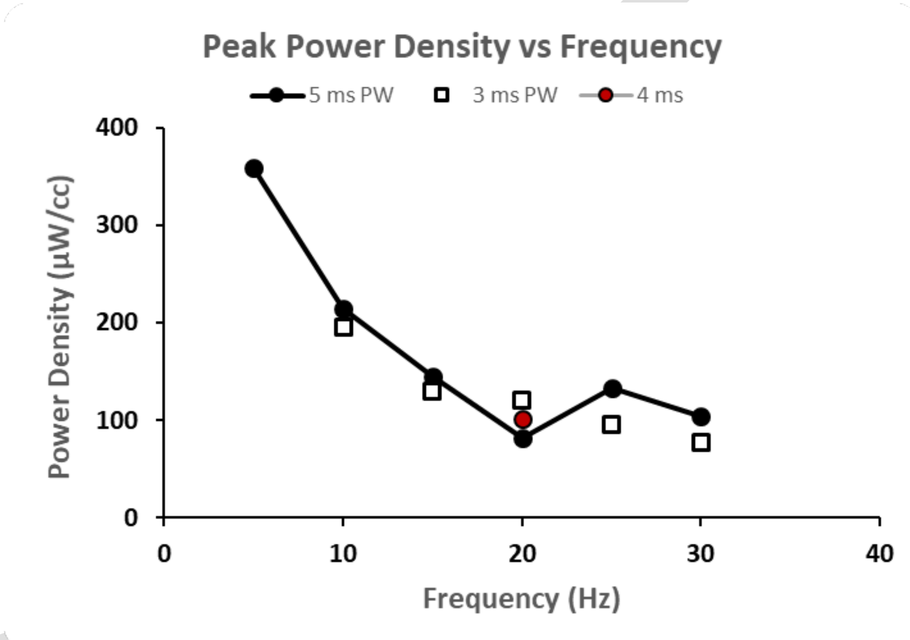

Figure 3-1 Peak Power Density Vs. Frequency Showing Ideal Pulse Frequency of 20 Hz

Lower average power density (µW/cm^3) is associated with a more efficient waveform for immobilization of Round Goby (Figure 3-2). For a 5 ms PW, 20 Hz was the most efficient frequency. There was less of a difference in average power density thresholds by frequency for waveforms with a 3 ms PW. The 20 Hz waveform with a 4 ms PW had the same efficiency as for the 20 Hz waveform with a 5 ms PW and almost the same efficiency as for the 20 Hz waveform with a 3 ms PW. A 20 Hz, 5 ms PW waveform was chosen for subsequent testing.

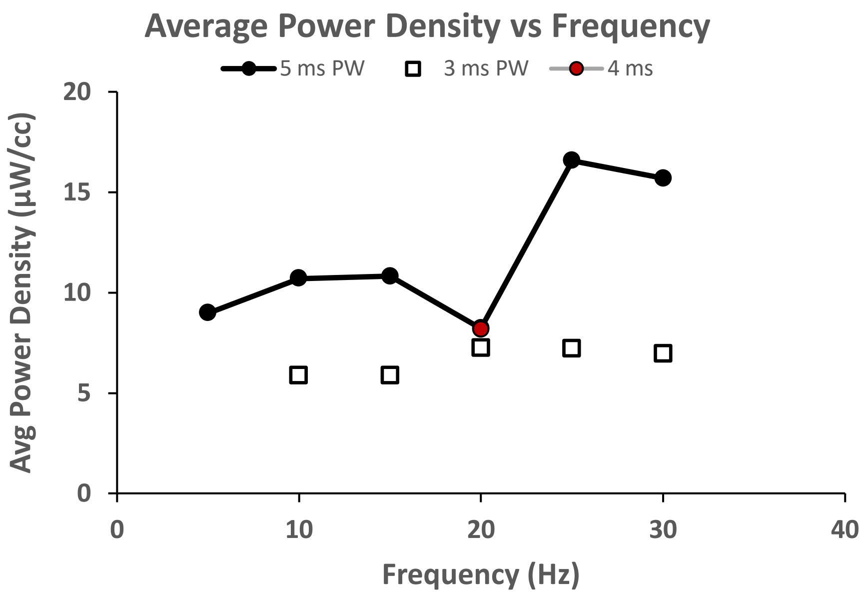

Figure 3-2 Average Power Density Vs. Frequency Showing Ideal Frequency of 20 Hz

Average power density for a pulsed direct current waveform is the RMS (root mean square) power density. Pulsed direct current RMS power is equivalent to alternating current RMS power in terms of heat dissipation and its ability to do work in a given time.

The second electric dose experiment component tested for an effect of temperature on the probability a fish will be immobilized. The logistic regression was assessed in R v3.6.1. Six models were constructed (Table 3-2). All models met Goodness of Fit (GoF), with the best in terms of dAIC, a model with a positive interaction effect between electric dose and fish length. The next best model was an additive model with electric dose and fish length, but it did not have an appreciably larger AIC score (dAIC 0.673). The additive model explained more deviance but had a smaller degrees of freedom (df). The top two models were nested and were assessed with a Chi-square test (p = 0.25) that found the more complex model ($V/cm + L$) was not warranted. As expected, the best model showed that the probability of immobilization is positively related to the applied voltage and fish length: $logit = -12.54 + \ 0.33(V/cm * L)$ (Figure 3-3).

Table 3-2 Temperature Effect Modelling Results

Note: Units For V Are volts/cm, L is Round Goby length in cm, and T is temperature in °C.

Model	Residual Deviance	df	GoF	AIC	dAIC	AUC
$V * L$	26.259	44	0.33	30.259	0	0.9432
$V + L$	24.932	43	0.25	30.932	0.673	0.9545
$V + L + V * L$	23.905	42	0.91	31.905	1.646	0.9545
$V + L + T$	24.795	42	0.24	32.795	2.536	0.9545
V	40.345	44	0.13	44.345	14.086	0.8778
$V + T$	40.229	43	0.47	46.229	15.97	0.8788

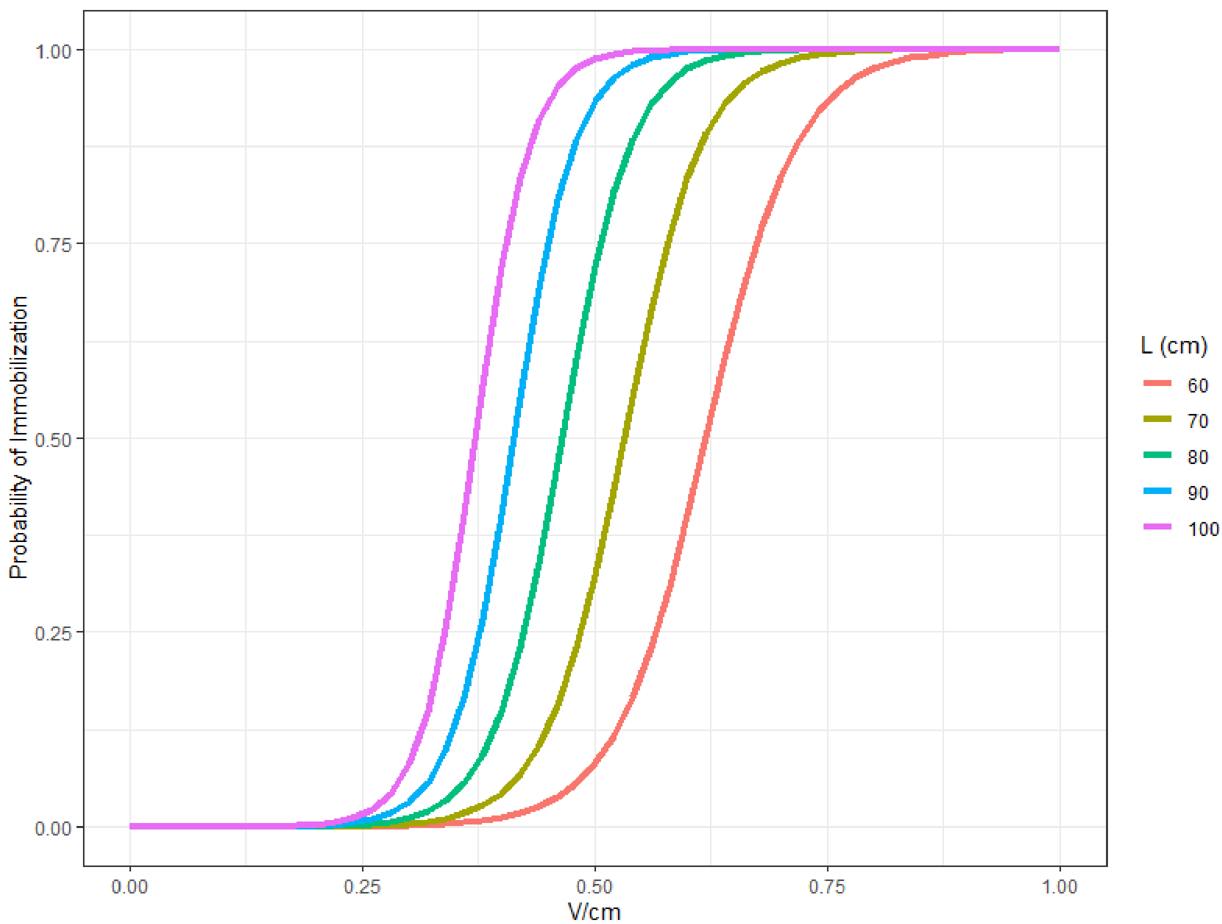

Figure 3-3 Predicted Probability of Immobilization for Increasingly Larger Fish as a Function of V/cm

Note: The larger fish get, the smaller the electric dose required for immobilization.

The final component was designed to quantify the electrical dose required to immobilize Round Goby. Voltage and exposure time were combined into a single dose parameter, Energy Density ($\mu J/cm$^3). The effect of Energy Density and total length on Round Goby immobilization was assessed using logistic regression in R v3.6.1. Three models were fit (Table 3-3), the best of which incorporated an interaction effect between energy dose and length, which serves to amplify the effect of the electric dose. Larger fish are more sensitive to electrical doses; they will become immobilized with higher probability than smaller fish at the same electrical dose (Figure 3-4). The best electric dose candidate model is given with: $logit = -3.582 + 0.001(E * L)$.

Table 3-3 Electric Dose Response Results

Note: Units for energy density (E) are in $\mu J/cm^3$ and units of total length (L) are in cm.

Model	Residual Deviance	df	GoF	AIC	dAIC	AUC
$E * L$	48.056	78	0.8339	52.056	0	0.9389
$E + L$	49.184	77	0.9835	55.184	3.128	0.9317
E	64.327	78	NA	68.327	16.271	0.9052

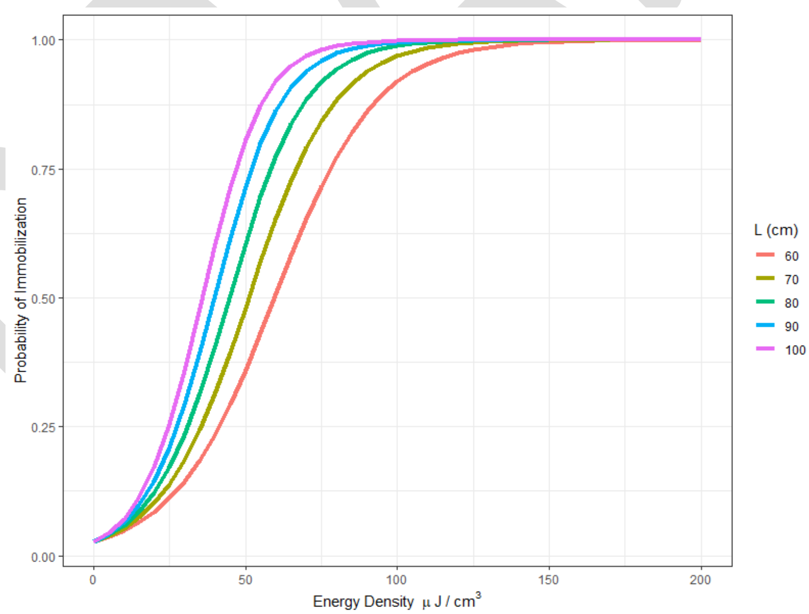

Figure 3-4 Predicted Probability of Immobilization for Increasingly Larger Fish as a Function of Energy Density

Note: The larger fish get, the smaller the electric dose required for immobilization.

In summary, the dose response experiments show that larger individual Round Goby are more easily immobilized than smaller individuals. The ability for an electrical field to immobilize a Round Goby individual increases with both higher energy and higher voltage. Differences in water temperature do not appear to affect immobilization of Round Goby individuals independently of the associated differences in water conductivity.

3.3 Swimming Study

The study team used 77 Round Goby to study the effect of water velocity on time until fatigue. Each fish was exposed to a constant velocity for 160 seconds, the length of time of which the locks are in operation. After the trial, the fish was allowed to recover, where most settled to the bottom of the tank with the aid of their modified pectoral fins. After a recovery period, the study team increased water velocity and then stimulated the fish to swim for another 160 seconds. The study team included a frailty term when analyzing the data to control for repeated measures because some fish are more susceptible to fatigue for underlying reasons (injury, disease, etc.). Time until fatigue was assessed with Cox Proportional Hazards Regression using the survival package in R v 3.6.1.

Three models were fit with frailty terms (Table 3-4) that investigated the effect of fish length and water velocity on the time until fatigue. The best model with lowest AIC (638.29) included both variables as additive terms with full interaction. The hazard ratio associated with a 1 unit increase in water velocity, was 1.43. In other words, for every increase in centimeter per second a fish is 1.43 times more likely to become fatigued. CoxPH also found a positive relationship with fish length. A fish that is 1 cm larger than another, is 1.4 times more likely to become fatigued. However, the hazard ratio associated with the interaction term was 0.98; suggesting that larger fish are more resistant to fatigue at higher velocities. This may be related to the Round Goby's modified pectoral fins. The survival package does not produce individual estimates for the frailty term for each fish, it only indicates whether or not we need to control for variability associated with repeated measures.

Models with frailty terms cannot be visualized with a cumulative incidence plot, therefore we fit another model strictly for plotting. This model should only be used for the purposes of visualizing the effect of increasing water velocity because it does not control for repeated measures. This model found that a Round Goby is 1.15 times more likely to become fatigued for every cm per second increase in water velocity. This estimate is more conservative than the model with frailty (1.15 vs 1.43). Figure 3-5 shows the proportion of Round Goby expected to become fatigued at time. If a water velocity of 50 cm per second can be maintained throughout the barrier for the duration of the lock operation (approximately 160 s), then 100% of Round Gobies will become fatigued.

Table 3-4 Time to Fatigue Model Results for Round Goby

Note: Model parameters are V For velocity (cm/s), L for fish length (cm), and F for frailty.

Model	LR	AIC	dAIC	Schoenfeld Residual (p-value)
V*L+F	<0.001	638.2975	0	0.56
V+F	<0.001	643.7157	5.4182	0.82
V	<0.001	699.7	61.4025	0.27
L+F	0.6	951.58	313.2825	0.95

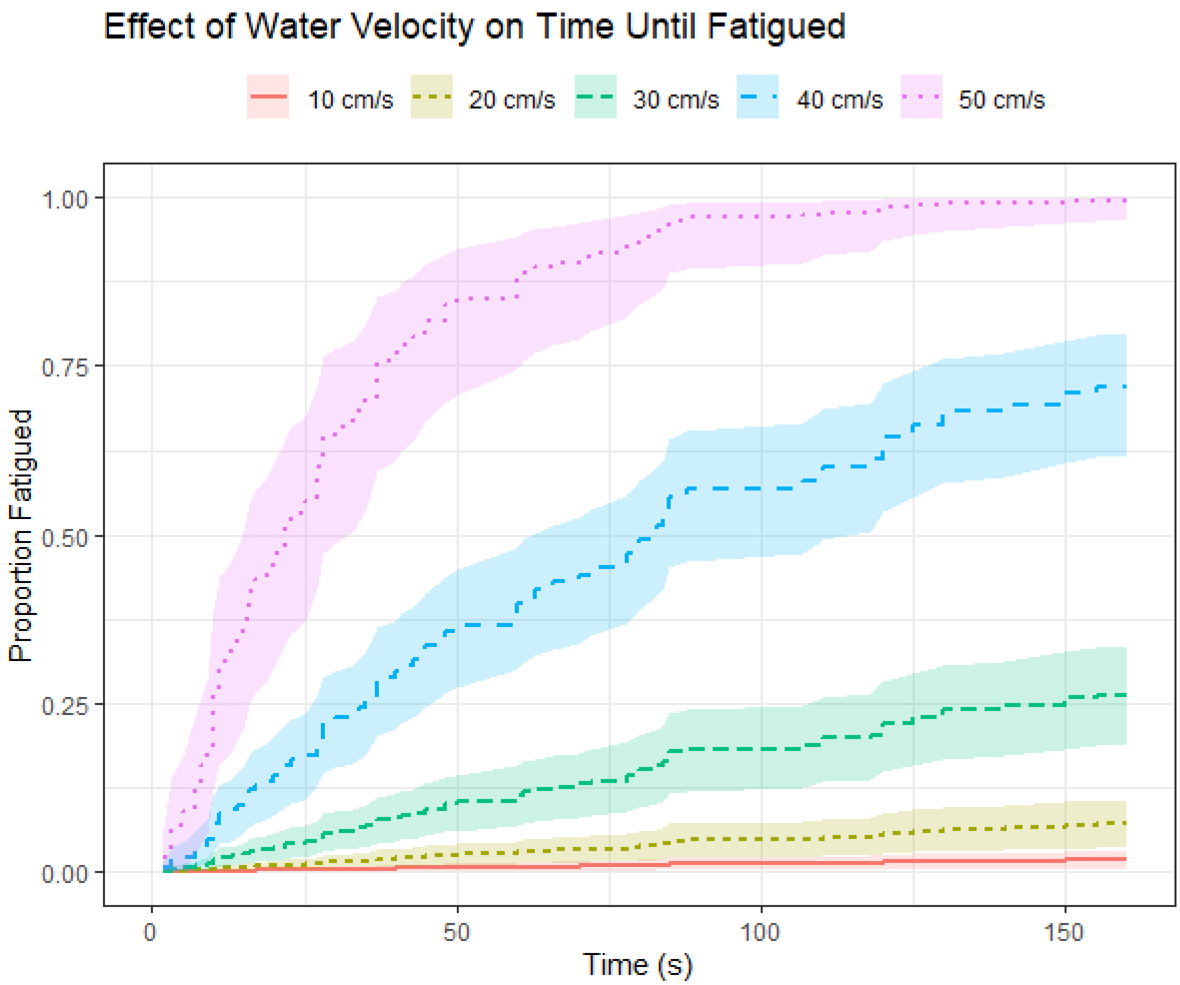

Figure 3-5 Proportion of Round Goby that Will Become Fatigued at Time as a Function of Increasing Water Velocity

Note: 100% of the fish will become fatigued at 150 seconds at a flow rate of 50 cm/s.

4.0 CONCLUSION

This study demonstrated the ability of electrical fields to immobilize adult Round Goby and quantified the effect water velocity has on the time until fatigue. Generally, as the electrical charge is increased, the probability that an adult Round Goby will exhibit the desired response (immobilization) also increases (Figure 2-3 and Figure 3-1). We found an amplification effect with fish length, where longer fish need less of an electrical dose. Of the fish assessed (54 mm – 152 mm), all will become immobilized at an Energy Density of 200 ($\mu J/cm$^3) (Figure 3-1).

The study team was also able to assess the effect of water velocity on the time until an adult Round Goby becomes fatigued. After controlling for repeated measures on each fish, we found that for every increase in cm/s, a fish is 1.4 times more likely to become fatigued. However, observations during testing demonstrated the Round Goby's ability to affix itself to nearly any substrate, where individual fish had to be stimulated to move at the beginning of each swimming trial.

These results show that the chosen technologies are capable of deterring adult Round Goby. Immobilization of smaller gobies and faster gobies requires more energy. These two findings may counter each other as smaller Round Goby individuals typically exhibit slower swim speeds than larger individuals and thus would remain inside an electric field for a longer period of time. Similarly, faster gobies typically have longer total lengths and are immobilized with lower levels of voltage and energy than smaller gobies.

This assessment cannot determine if the operating parameters we have identified are feasible from an engineering or fiscal perspective. What is clear though, is that the normal operation of Menasha Lock should coincide with regular removal of debris collecting in and around the electric barrier due to the proclivity of the Round Goby to utilize velocity refugia. A well-maintained barrier is an efficient and effective barrier.

5.0 REFERENCES

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