FACTORS FACILITATING ROUND GOBY (*NEOGOBIUS MELANOSTOMUS*) RANGE EXPANSION IN THE DES PLAINES RIVER WATERSHED ILLINOIS, USA

By

Matthew Allen Sarver

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ABSTRACT

The Round Goby (Neogobius melanostomus) is an invasive species of fish accidentally introduced to the Great Lakes drainage in the early 1990s. The species has since expanded its range into the Mississippi River watershed through the Chicago Sanitary and Ship Canal. The Midwest Biodiversity Institute (MBI) has observed expansion in the Des Plaines River and its tributaries beginning in 2014. I compared densities of Round Goby to habitat conditions and select analytes to determine what factors are contributing to colonization and proliferation in these new localities. The selected model indicates habitat conditions, nitrates, conductivity, total Kjeldahl nitrogen (TKN), total suspended solids (TSS), temperature, (D.O.) were all significant. Poor quality habitat, high concentrations of TSS and TKN are not well tolerated, while high concentrations of nitrates, low D.O., high temperatures, and high specific conductance were tolerated by Round Goby.

CHAPTER ONE

INTRODUCTION

Invasive species negatively impacted North American ecosystems and the economies they support. The mechanisms of invasive species expansion into new ecosystems include a purposeful or accidental introduction, and subsequent movement through natural modes. Invasive, generally non-native, fish have entered North American water bodies through intentional introductions as part of stocking programs, vegetation control or unauthorized releases, and accidental introductions through trade, aquaculture, or bait bucket releases (Orth 2018; Rice and Zimmerman 2019; Trautman 1981; Marsden and Jude 1995). Zebra mussels (*Dreissena polymorpha*) and Round Goby (*Neogobius melanostomus*) have been transported from their native waters to the Great Lakes via commercial shipping, and Silver Carp (*Hypophthalmichthys molitrix*), Bighead Carp (*Hypophthalmichthys nobilis*), and Grass Carp (*Ctenopharyngodon idella*) were stocked in private lakes and ponds to limit algae and aquatic macrophytes. All the species have been collected in the Des Plaines River and/or Lake Michigan, and have negative effects on native fauna. Round Goby eat the eggs of sports fish and compete with juvenile Smallmouth Bass, Silver and Bighead Carp consume zooplankton which is a vital food source for larval fish, and zebra mussels out compete native mussels for space and food (Metzke 2022, Snyder 1994).

These invasive species affect the Upper Mississippi River and Great Lakes watersheds. The Chicago Sanitary and Ship Canal (The Canal) facilitated the introductions of invasive fish into and out of the Great Lakes. The Canal was completed in 1900 to connect Lake Michigan to the Illinois and Mississippi Rivers via the Des Plaines River. It was designed to both divert pollution away from Lake Michigan and allow trade between the Lake and the Mississippi River drainage. Since 1907, The Canal not only provided passage for ships between these major trade routes, but it also provided passage for organisms. The Canal is the connection between the Mississippi River watershed and the Great Lakes, each containing fisheries worth billions of dollars (Wines 2014).

Round Gobies are a benthic fish species native to the Caspian and Black Seas and have been introduced across Europe and the United States (Figure 1). The expansion of this species has been likely facilitated by international trade through marine transport (Roche et al. 2015; Marsden and Jude 1995; Rice and Zimmerman 2019). Introduced into the Great Lakes through the release of eggs or juveniles from the hulls or ballast water of commercial ships the species was first observed in the early 1990s in the St. Clair River (Marsden and Jude 1995; Hayden and Miner 2009). Round Gobies have established populations in each of the Great Lakes and many of their tributaries (MBI 2018 and 2022; Metzke et al. 2022), like the Illinois River watershed (MBI 2018 and 2022; Rice and Zimmerman 2019; Metzke et al. 2022).

Figure 1. A male Round Goby (Neogobius melanostomus) was collected in the Des Plaines River mainstem upstream of the confluence of the Chicago Sanitary and Ship Canal in 2018.

The Round Goby range is expanding in the Des Plaines River where it was initially observed by the United States Fish and Wildlife Service and into the middle Illinois River by the Illinois Natural History Survey in 2004 (Irons et al. 2006; Figure 2a). Introduction to the Des

Plaines River occurred through the movement from the Chicago Sanitary and Ship Canal. Further observations have been made in the Des Plaines River mainstem and its tributaries with extensive records from observations in major tributaries such as the DuPage River and Salt Creek by the Midwest Biodiversity Institute (MBI) beginning in 2015 (MBI 2018 and 2022; Figure 2b).

In their native range and areas of invasion Round Goby typically prefer habitats that provide course substrates with interstitial spaces to hide, hunt prey, and build nests (Ray and Corkum 2001; Brownscombe and Fox 2012; Reid 2019). As a euryhaline species, Round Goby inhabit environments that range in salinity, including freshwater streams and brackish seas. Where observed in flowing water, slow and moderate flows are preferred where coarse substrates and aquatic macrophytes are available (Ray and Corkum 2001; Taborelli et al. 2008). This ability to inhabit a wide range of salinities and both lotic and lentic ecosystems is a testament to the ability of the species to expand its range in novel ecosystems.

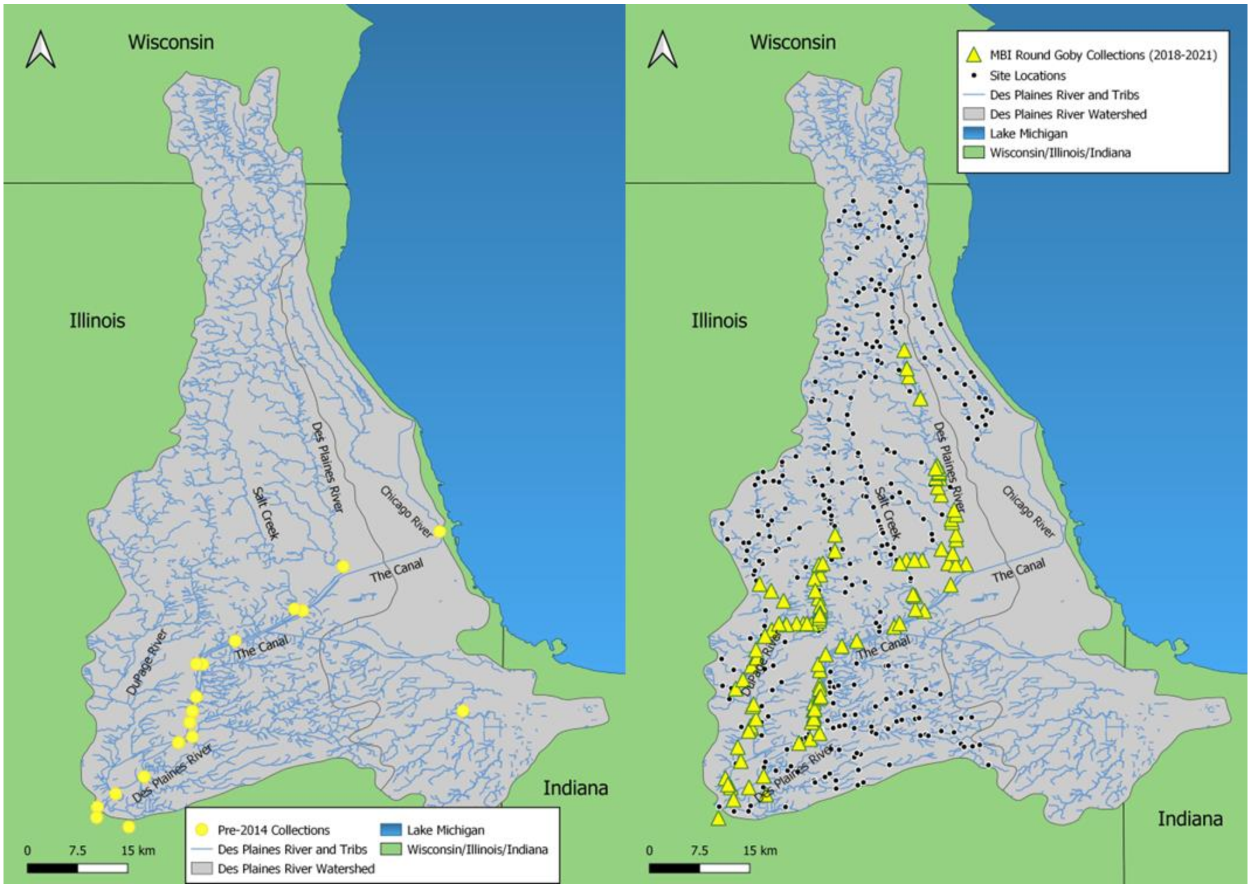

Figure 2. Maps of the Des Plaines River and Chicago River watershed in NE Illinois. Rivers and streams are depicted as blue lines, The Lake Michigan and Des Plaines River watershed boundary is a dark gray line. The Illinois Michigan Canal and Chicago Sanitary and Ship Canal connect the two watersheds. The left map uses yellow dots denote the locations where Round Goby were collected by US FWS, INHS, and IDNR be 2014 (a). The right map depicts sites sampled for fish, habitat, and water chemistry from 2018-2021 are denoted as black dots and yellow triangles denote sites where Round Goby were collected by MBI (b).

Round Goby expansion in the Des Plaines River and throughout its tributaries has been documented by the Illinois Department of Natural Resources (IDNR), the Illinois Natural History Survey (INHS), and MBI (MBI 2016, 2017b, 2018). Neither the water chemistry nor the habitat and water quality parameters that facilitate their expansion are fully understood. The species is known to be tolerant of heavy metal pollution, and some aspects of its preferred habitat have also been studied (Taraborelli et al. 2008; McCallum et al. 2014; Reid 2019). However, the lack of information in lotic systems that are dominated by urban and agricultural land uses with effluent-dominated systems, and the range in degree of modification for anthropogenicuses has not yet been fully studied. Siltation, channelization, water temperature, nutrient enrichment, organic enrichment, dissolved oxygen, pH, and chlorides influences are continuous problems in the Des Plaines River and its tributaries, stemming from urban and agricultural land uses. These respective issues can limit the abundance of fish species of varying tolerances from inhabiting respective stretches of streams or streams in their entirety, in many cases to the point of total exclusion. Round Goby tolerances to these types of pollution are relatively unknown nor is it known to what degree they facilitate the expansion and colonization of the species.

Therefore, the Round Goby populations of the Des Plaines River provide an opportunity to explore the relationship between an invasive fish species that can inhabit a wide range of environments, pollution types originating from both urban and agricultural land uses, and lotic habitat conditions. Here I detail the expansion of the species through a watershed which the rivers and streams were altered for commerce, flood control, and recreation while having pollutants input from numerous point- and nonpoint sources. This path helped answer the questions: 1) What habitat conditions are preferred by Round Goby? 2) How tolerant this species is to water quality conditions?; and 3) At this critical nexus between two important watersheds, can we manage our urban aquatic systems to increase resilience to non-native, invasive species?

CHAPTER TWO

MATERIALS AND METHODS

Study Area

The Des Plaines River originates in southern Wisconsin, flowing 214 km south through Chicago before turning southwest toward its confluence with the Kankakee River near Channahon, IL. More than 3218 km^2 of its watershed is located within the state of Illinois and includes major tributaries such as Salt Creek, the DuPage River, and the Chicago Sanitary and Ship Canal (see Figure 2). Urban, industrial, agriculture, suburban, park, wetland, and forest account for the majority of the land uses in the watershed. Free-flowing for nearly 185 km from its headwaters to the confluence with the Chicago Sanitary and Ship Canal, the final 25.7 km are heavily influenced by the Brandon Locks and Dam in Joliet, IL as well the Dresden Locks and Dam on the Illinois River.

The Des Plaines River provides a range of substrate types including silt, muck, detritus, sand, gravel, cobble, bedrock, boulders, aquatic macrophytes, rip-rap, and woody debris for cover. Major tributaries such as the DuPage River, Salt Creek, Mill Creek, and Hickory Creek also provide a wide range of substrate and cover types for Round Gobies to inhabit. The Des Plaines River is also heavily influenced by anthropogenic alterations to its chemical integrity. Nutrients, metals, volatile organic compounds (VOCs), salts, and other compounds have all increased with the expansion of Chicago and agriculture.

Fish, habitat, and water chemistry were sampled from 2018 through 2021 at more than 400 locations by MBI. Sites included the upper Des Plaines River watershed located in Lake and northern Cook Counties, Illinois, the East Branch of the DuPage River watershed located in DuPage and northern Will Counties, Illinois, the West Branch DuPage River watershed located in DuPage County, Illinois, Salt Creek in eastern DuPage and western Cook Counties, Illinois, the Lower DuPage River watershed in Will County, Illinois, the lower Des Plaines River watershed in Will and Cook Counties, Illinois, and the North Branch Chicago River watershed located in southern Lake and northern Cook Counties, Illinois (Figure 2).

Fish

Fish were collected using pulsed DC electric current. Headwater sites (<52 km^2 drainage area) were sampled at a distance of 0.15 km in an upstream direction using a bank-set longline electrofishing configuration or a Wisconsin AbP-3 battery-powered backpack electrofishing unit. The bank-set longline was powered by a 2500-Watt Honda generator, and the electric current was controlled using a Smith-Root 2.5 generator-powered pulsator (GPP) control box. Wading sites (52-1295 km^2 drainage area) were sampled at a distance of 0.20 km in an upstream direction using a tote-barge configuration. The gear was powered by a 2500-Watt Honda generator, and the electric current was controlled using a Smith-Root 2.5 GPP control box. Boat sites (388-15,540 km^2 drainage area) were sampled at a distance of 0.5 km in a downstream direction using a 4.88-meter inflatable raft or a 4.88-meter aluminum jon boat. The production of the electric current for boatable gear was achieved through either a Smith-Root 5.0 GPP control box powered by a 11.0 HP generator with a 5000-Watt alternator or a 5.5 HP generator with a 2500-Watt alternator. Fish were collected with a dip net and deposited into a 121 liter live-well that was aerated by a 12-volt air compressor powered by a deep cycle marine battery until the end of the site.

All sites were sampled by a two-to-three-person crew consisting of a fish crew leader and one or two field technicians. Fish were identified to species, weighed, and counted before being returned to the water. Fish that were not identified in the field were preserved in a 10% formaldehyde solution and processed in the lab.

Habitat

I evaluated the habitat at each site using the Qualitative Habitat Evaluation Index (QHEI; Rankin 1989; Ohio EPA 2006). The QHEI is divided into seven categories: substrate type and quality, riparian quality, instream cover type and quality, pool-riffle-run quality, riffle quality, and gradient. Each category quantifies important aspects of both instream and riparian habitat quality for fish assemblages. The sum of the metrics provides an overall habitat score for each site that ranges from 0 to 100.

Water Chemistry

Water samples were collected by each watershed group at the same, predetermined sites where fish collection occurred following Illinois EPA protocols (2012). Chemical laboratory analyses were provided by certified labs. Water samples were primarily collected from May through November with select sites having samples collected during each month of the year (MBI 2016, 2017a, 2017b, 2018, 2020). Multiple samples were collected at each site during the course of a sampling season for each survey. Water quality parameters such as ammonia, nitrate, phosphorus, dissolved oxygen (D.O), total suspended solids (TSS), total dissolved solids (TDS), chloride, and conductivity.

Statistical Methods

Data analysis aimed to determine what water chemistry composition (analytes) and habitat conditions are most conducive for Round Goby populations to establish and persist in the Des Plaines River watershed. Median values were used for each analyte in an effort to mitigate the effects of outliers.

I created a correlation plot to analyze the relationship between the independent variables and Round Goby abundance. With the use of a variation of inflation factor (VIF) I measured multicollinearity between independent variables. In order to determine the true relationships between the dependent and independent variables, I tested VIFs were tested on a saturated model to avoid skewed or misleading results from the standardized independent variables in the R:Cran Car Package (Fox and Weisberg 2019). Following guidance from Fox and Weisberg (2019), if the VIF value was between 0 and 2 there is a lack of collinearity, while VIF values over 2 are considered collinear.

The Poisson Regression was selected to analyze the relationship between analytes and habitat conditions to Round Goby abundance at a location.

$$\text{Log}(\lambda_i) = \beta_0 + \beta_1 x_{i1} + \ldots. + \beta_n x_n \quad \text{(Equation 1)}$$

Where: $\text{Log}(\lambda_i)$ is the log of mean number of Round Goby, β_0 is the model intercept, B_j are the coefficients of independent variables, and xi are the predictor variables .

A list of 31 generalized linear models (GLMs) using the Poisson method was formulated to test the best-fitting model for ascertaining the reasoning for Round Goby presence and abundance after removing the independent variables with high collinearity. Potential GLMs were analyzed using Akaike’s information criterion (AIC). The formula for determining the most appropriate model is:

$$\text{AIC} = -2*\text{log-likelihood} + k*\text{npar} \quad \text{(Equation 2)}$$

Where: AIC is the Akaike's Information Criterion, k is the number of independent variables, and npar is the number of parameters in the fitted model

I selected the model with the lowest AIC as the most appropriate to describe the relationship between the number of Round Goby collected during a sample and the independent variables.

To determine the proportion of the variance that was explained by the selected independent variables a pseudo R^2 was calculated to determine the goodness of fit for the selected model. The pseudo R^2 was used because Poisson regression does not provide an R^2.

$$R^2 = (D_0 – D)/D_0 \qquad \text{(Equation 3)}$$

Where: R^2 is the coefficient of determination, D_0 is the deviance of the null model, and D is the residual deviance

I used logistic regression to create receiver operating characteristic (ROC) curves to determine quality of calculated thresholds (Appendix A). ROC were derived using R:Cran to determine the coordinates that described the threshold for each significant independent variable where:

True Positive Rate = True Positive/True Positive + False Negative

False Positive Rate = False Positive/False Positive + True Negative

Area under the curve (AUC) for the ROC curves were calculated using the auc function using the R:Cran pROC (Robin et al. 2011). I used the AUC to determine the usefulness of the logistic regression model.

CHAPTER THREE

RESULTS

Correlation Plot

The correlation between the number of Round Goby, habitat quality, and analytes is depicted in Figure 3 for the Poisson regression. The highest correlations (R-value) between the number of Round Goby and the independent variables were conductivity (0.21), total suspended solids (TSS) (-0.24), and nitrates (0.36). Chlorides (0.08), ammonia (-0.10), and QHEI (0.09) had the lowest correlation to the number of Round Goby. Chlorides and total dissolved solids (TDS) were closely and positively correlated (0.82). This high collinearity indicates that the two variables are not independent and should be removed from the analysis. The two variables were omitted from model analysis based on this factor. No other set of variables had a correlation value above 0.66 (pH and dissolved oxygen (D.O.). An interesting relationship between drainage area, TDS, chlorides, conductivity, and temperature can be observed in the correlation plot (Figure 3). As the drainage area increases TDS, chlorides, and conductivity decrease, while water temperature increases. Dilution of TDS and chlorides from greater volumes of water occurs in larger drainage areas, which lowers the specific conductance. Also, riparian zones have been removed through much of the watershed, exposing surface water to direct sunlight and its retention time in the watershed.

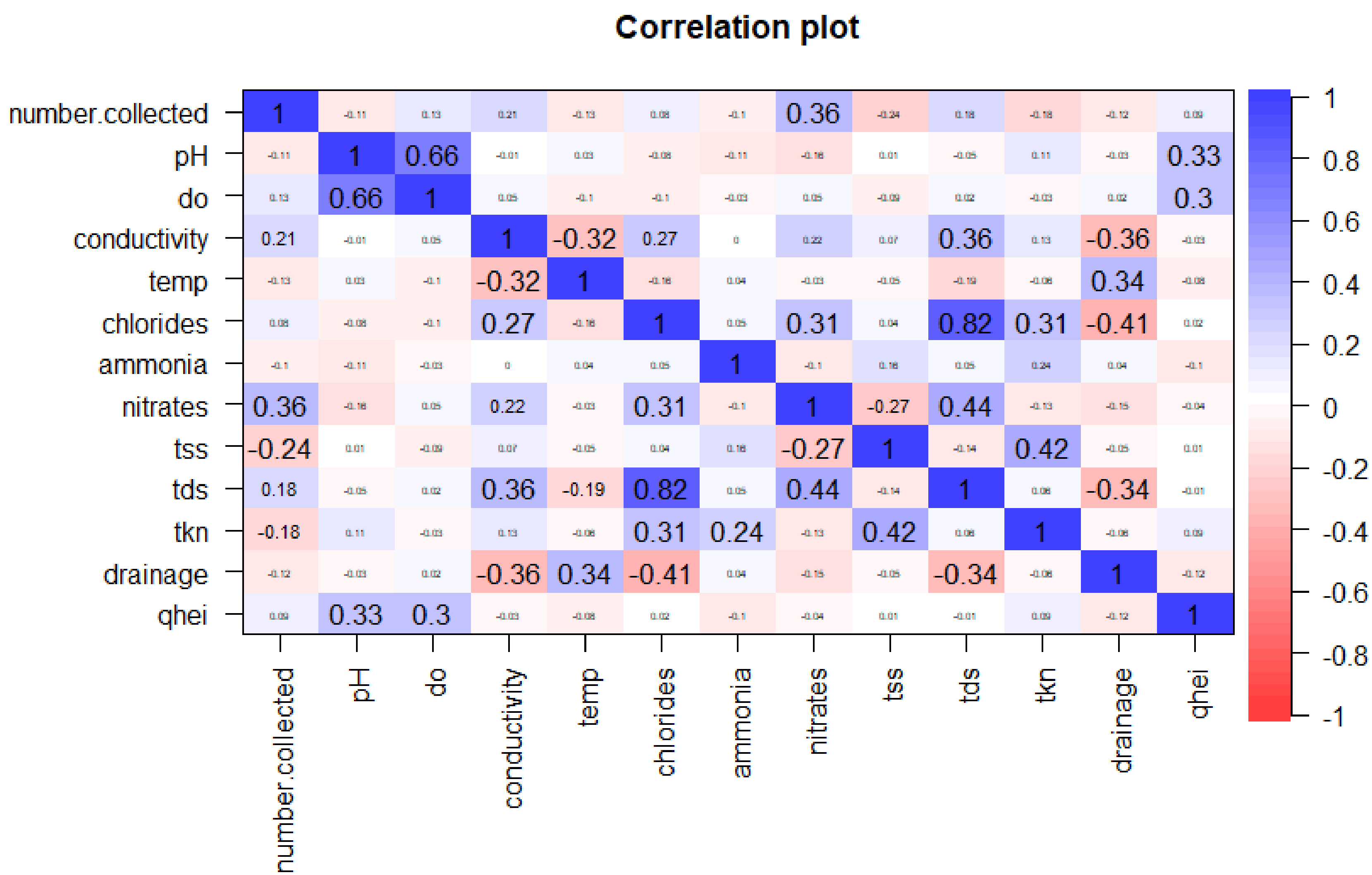

Figure 3. Correlation plot between the number of Round Goby collected, habitat quality, and select analytes. Blue rectangles indicate a positive relationship, and red rectangles indicate a negative relationship.

Based on the results of the logistic regression, significant variables were nitrates (0.313, p-value = 3.45e-6), TSS (-0.273, p-value = 5.72e-5) D.O. (0.166, p-value = 0.016), QHEI score (0.211, p-value = 0.002), cover score (0.279, p-value = 3.90e-5), riparian score (0.156, p-value = 0.023), and sequence score (0.335, p-value = 6.19e-7) (Table 3). All other variables were insignificant in determining whether Round Goby were present at a site.

Table 1. The correlation, p-value, t-value, and degrees of freedom for the independent variables and Round Goby presence. Bold text indicates the independent variable is significant to the number of Round Goby present at a site.

Variable	p-value	Correlation	t-value	Df
Nitrates	**$3.45e^{-6}$**	0.313	4.77	209
Total Suspended Solids	**$5.72e^{-5}$**	-0.273	-4.11	209
Total Dissolved Solids	0.555	0.041	0.590	209
Conductivity	0.165	-0.096	-1.39	209
Total Kjeldahl Nitrogen	0.331	-0.067	-0.974	209
pH	0.112	0.110	1.59	209
Temperature (°C)	0.219	0.085	1.23	209
Chlorides	0.398	-0.058	-0.847	209
Ammonia	0.938	-0.005	-0.078	209
Dissolved Oxygen	**0.016**	0.166	2.44	209
Habitat Score	**$2.00e^{-2}$**	0.211	3.11	209
Cover Score	**$3.90e^{-5}$**	0.279	4.20	209
Riparian Score	**0.023**	0.156	2.29	209
Riffle Score	0.640	0.032	0.468	209
Gradient Score	0.065	0.127	1.86	209
Channel Morphology Score	0.812	0.016	0.238	209
Pool-Current Quality	**$6.19e^{-7}$**	0.335	5.14	209
Drainage Area (sq. mi.)	0.053	0.133	1.94	209

Round Goby are likely sensitive and tolerant to different analyte concentrations or habitat conditions that limit or exclude Round Gobies from a site. Thresholds were calculated for the significant variables in Table 1 from the ROC curve for each significant variable to determine at what concentration (Table 2).

Table 2. Derived threshold values for analytes and habitat metrics for Round Goby in the Des Plaines River drainage.

Variable	Threshold
Dissolved Oxygen	6.845
Total Suspended Solids	16.25
Nitrates	2.475
QHEI	67.12
Cover Score	15.50
Riparian Score	4.625
Sequence Score	6.500

Model Evaluation

The GLM models tested and the k, AIC, AICc, d.AICc, w.AICc, and evidence rating values are recorded in Table 3. The lowest AICc is associated with the model that fits the true data with the fewest variables (Acquah 2009). The most appropriate model had an AIC of 5702.838, and an AICc of 5714.088.

N = QHEI + TSS + TKN + Ammonia + Conductivity + Temperature + Nitrates + D.O.

Where: N is the number of Round Goby at a location, QHEI is the overall qualitative habitat evaluation index score for a sample, TSS is the TSS concentration at a location in mg/L, Nitrates is the nitrates concentration at a location in mg/L, DO is the dissolved oxygen concentration in mg/L, and Conductivity is the specific conductance (μS/cm), Ammonia = ammonia concentration (mg/L), Temp = water temperature (°C), TKN = total Kjeldahl nitrogen concentration (mg/L).

Table 3. Generalized linear models (GLMs) derived from the habitat and chemical independent variables collected from sites in the Des Plaines River watershed ordered by the Akaike information criterion (AIC).

	Models	**k**	**AIC**	**AICC**	**d.AICC**	**w.AICC**	**evid.rat**
1	qhei + tss + tkn + ammonia + conductivity + temp + nitrates + do	9	5702.838	5714.088	0	0.923304153	1
2	qhei + drainage + tss + tkn + ammonia + conductivity + temp + nitrates + do	10	5704.397	5719.064	4.976222	0.076695847	12.03851567
3	drainage + qhei + tss + ammonia + conductivity + do + temp + nitrates	9	5780.473	5791.723	77.63586	1.28E-17	7.22E+16
4	qhei + drainage + tss + nitrates + tkn * do	8	5874.388	5882.859	168.7715	2.08E-37	4.45E+36
5	qhei + drainage + tss + nitrates + tkn * do	8	5874.388	5882.859	168.7715	2.08E-37	4.45E+36
6	qhei + drainage + tss + nitrates + tkn * do	8	5874.388	5882.859	168.7715	2.08E-37	4.45E+36
7	tss + tkn + ammonia + conductivity + temp + nitrates + do	8	5901.458	5909.928	195.8406	2.75E-43	3.36E+42
8	drainage + tss + tkn + ammonia + conductivity + temp + nitrates + do	9	5900.271	5911.521	197.4334	1.24E-43	7.45E+42
9	drainage + tkn + tss + ammonia + conductivity + do + temp + nitrates	9	5900.271	5911.521	197.4334	1.24E-43	7.45E+42
10	qhei + tss + tkn + nitrates + do	6	5913.562	5917.983	203.8951	4.90E-45	1.88E+44
11	qhei + drainage + tss + nitrates + do	6	5920.344	5924.765	210.6775	1.65E-46	5.60E+45
12	qhei + nitrates + tss + tkn	5	5949.891	5952.891	238.8033	1.29E-52	7.17E+51
13	qhei + tss + nitrates + do	5	5950.825	5953.825	239.7379	8.07E-53	1.14E+52
14	qhei + tss + nitrates + do	5	5950.825	5953.825	239.7379	8.07E-53	1.14E+52
15	qhei + tss + nitrates + do	5	5950.825	5953.825	239.7379	8.07E-53	1.14E+52
16	qhei + do + nitrates + tss	5	5950.825	5953.825	239.7379	8.07E-53	1.14E+52
17	qhei + nitrates + tss	4	5986.79	5988.695	274.6074	2.16E-60	4.27E+59
18	tss + ammonia + conductivity + nitrates + do	6	6033.822	6038.243	324.1555	3.77E-71	2.45E+70
19	drainage + tss + nitrates + tkn + do	6	6049.342	6053.763	339.6754	1.61E-74	5.75E+73
20	drainage + tss + nitrates + tkn + do	6	6049.342	6053.763	339.6754	1.61E-74	5.75E+73
21	drainage + tss + nitrates + do	5	6068.091	6071.091	357.0033	2.77E-78	3.33E+77
22	tss + do + nitrates + drainage	5	6068.091	6071.091	357.0033	2.77E-78	3.33E+77
23	tss + tkn + nitrates + do	5	6091.814	6094.814	380.726	1.96E-83	4.72E+82
24	tss + tkn + nitrates + do	5	6091.814	6094.814	380.726	1.96E-83	4.72E+82
25	tss + do + nitrates	4	6112.122	6114.027	399.9395	1.32E-87	7.01E+86
26	drainage + nitrates + tss	4	6160.209	6162.114	448.0264	4.76E-98	1.94E+97
27	qhei + nitrates	3	6932.446	6933.537	1219.45	1.46E-265	6.31E+264
28	qhei + tkn + ammonia + conductivity + temp	6	7147.287	7151.708	1437.62	6.16760995271445e-313	Inf
29	1	1	8311.481	8311.647	2597.56	0	Inf
30	qhei	2	8213.961	8214.482	2500.395	0	Inf

Variation Inflation Factor (VIF)

The VIF values for the saturated models contained multiple variables with collinearity above two (Table 4). This could potentially lead to performance issues with the model, so TDS, pH, and Chlorides were removed from the saturated model. A VIF analysis was not performed on the variables for logistic regression, as each variable was analyzed individually.

Table 4. The VIF values for each independent variable in the saturated model. Chlorides and TDS are known to have a close relationship with conductivity, and pH had high collinearity with D.O., so they were removed to create the final model.

QHEI	Drainage	TSS	Nitrates	D.O.	TKN	Ammonia	Conductivity	Temperature	TDS	Chlorides	pH
1.338	1.453	1.348	2.271	2.801	2.099	1.258	2.015	1.291	6.092	6.251	3.706

The VIF values for each variable in the selected model fall below the exclusion threshold of 2 (Table 5). The low VIF values indicate that the variables are not correlated and independent, meaning multicollinearity is limited or absent from the final model.

Table 5. The VIF values for each variable in the selected model are all below 2, indicating that all variables are acceptable.

QHEI	TKN	TSS	Nitrates	D.O.	Ammonia	Conductivity	Temperature
1.282	1.272	1.242	1.335	1.101	1.110	1.600	1.124

Model Performance

The dispersion parameter value of 1 is near the ideal σ, so the variance does not increase faster than the mean, indicates low fluctuation around the mean of the data, and that the model can be trusted to predict Round Goby numbers at a site. Despite the low dispersion of the model, the calculated pseudo R^2 of 0.343 indicates a weak effect of the model when determining Round Goby abundance.

The model results are very convincing (p-value < $2.00e^{-16}$) in determining the number of Round Goby at a site (Table 5). Seven of the eight independent variables were significant in the model ($p<0.05$; Table 6). The most significant variables are **nitrates** (p-value < $2.00e^{-16}$), **QHEI** (p-value < 2.00e^{-16}), **TSS** (p-value < 2.00e^{-16}), **TKN** (p-value < 2.00e^{-16}), **conductivity** (p-value < 2.00e^{-16}), **temperature** (p-value = 3.27e^{-14}), and **D.O.** (p-value = 2.09e^{-07}). Ammonia concentration was not significant (p-value = 0.6900) to the model. There is very convincing evidence that the model can determine the number of Round Goby at a site (p-value <0.0001; Table 6).

Table 6. The coefficients, standard errors, t-values, and p-values for the model and independent variables. Also listed are the Null Deviance, Residual Deviance, and Dispersion Parameter.

	Estimate	**Std. Error**	**Z value**	**p-value**
(Intercept)	2.46E+00	2.39E-02	103.304	< 2e-16
qhei	2.79E-01	1.81E-02	13.904	< 2e-16
temp	-1.37E-01	5.22E-03	-7.587	3.27E-14
tss	-8.44E-01	4.07E-02	-20.734	< 2e-16
nitrates	3.50E-01	1.45E-02	24.069	< 2e-16
do	7.83E-02	1.51E-02	5.191	2.09E-07
tkn	-1.60E-01	1.79E-02	-8.955	< 2e-16
ammonia	-8.86E-03	2.22E-02	-0.399	0.69
conductivity	1.72E-01	1.76E-02	9.8	< 2e-16
Dispersion Parameter: Taken to be 1				
Null deviance: 7652.7 on 210 degrees of freedom				
Residual deviance: 5028.0 on 202 degrees of freedom				
Number of Fisher Scoring iterations: 6				

Round Goby Collections

The data in this paper focused on the expansion of Round Goby after the initial observations in 2014 and 2015 in the DuPage River watershed because the species had not fully established a population. Of the 400 sampling locations, 196 were conducted above a dam suspected of impeding fish passage (Figure 4). A total of 3,815 Round Goby individuals were collected at the remaining sampling locations in the Des Plaines River watershed. Small river sites were the most numerous (n=121), followed by headwater (n=42), wading (n=27), and large river (n=14; Figure 6). A total of 2,324 individuals were collected at small river sites from 2016 to 2021 (19.21 individuals/sample), 226 individuals at headwater sites (5.38 individuals/sample), 1,236 individuals at wading sites (45.78 individuals/sample), and 29 individuals during large river samples (2.07 individuals/sample; Figure 6).

Figure 4. The Fallwell Dam located on the West Branch DuPage River is one of several barriers to fish passage in the Des Plaines River watershed. Others include the Fullersburg Dam on Salt Creek, and the Pilcher Dam on Hickory Creek.

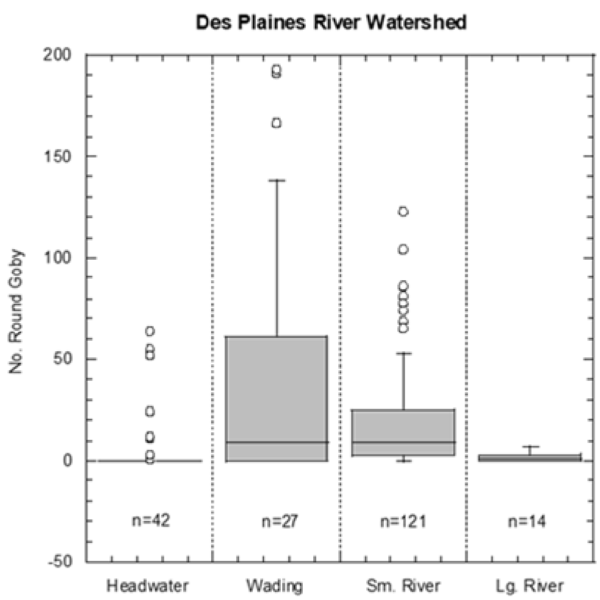

Figure 5. The range of number of Round Goby collected at headwater, wading, small river, and large river sites. The number of samples in each category is listed below each plot. The box and whisker plots depict the quartiles and outliers for the number of Round Goby collected at a site for each stream size.

Nitrates

In the Des Plaines River watershed, median nitrate concentrations ranged from 0.16 mg/L to 19 mg/L. Round Goby densities were significantly correlated to by nitrate concentrations ($p=2.00e^{-16}$), where higher concentrations of nitrates supported higher numbers of Round Goby (Figure 6).

The logistic regression model for Round Goby presence in relation to nitrates concentration indicates a preference for the species to inhabit sites that contain high nitrate concentrations. The threshold of 2.475 mg/L is relatively low compared to the observed values in the Des Plaines River watershed. Most Round Goby collections occurred at sites possessing concentrations well above that level (Figure 7). The logistic regression model for nitrates is in agreement with the Poisson model, indicating high nitrate concentrations are preferred to Round Goby (Figure 7).

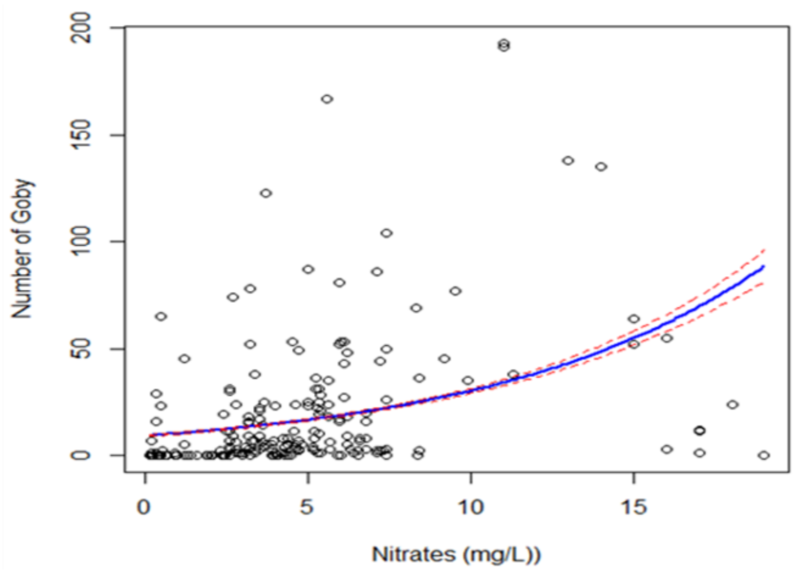

Figure 6. The relationship between the number of Round Goby and the median concentration of nitrates. The higher the concentrations of nitrates, the more Round Goby individuals are observed at a site. The blue line represents the logarithmic relationship between Round Goby and nitrate concentrations, and the red-dashed lines are the 0.95 confidence intervals.

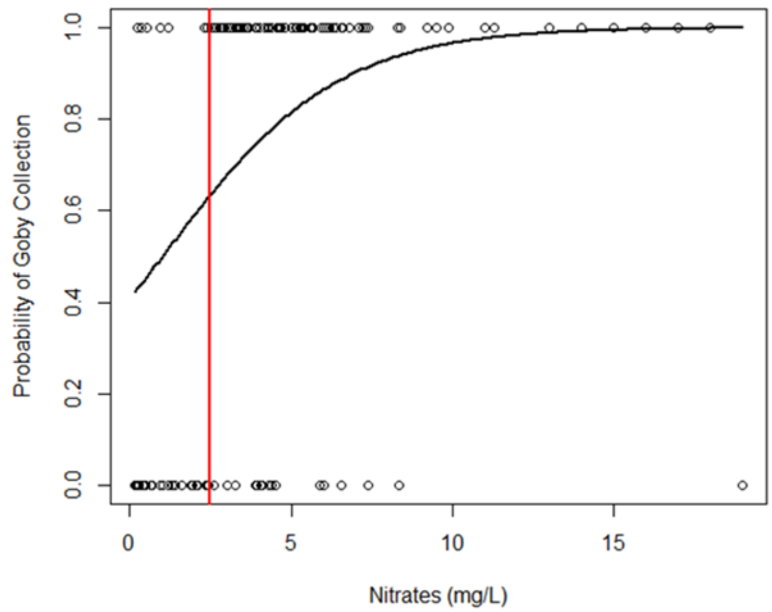

Figure 7. Higher nitrate concentrations increased the likelihood of Round Goby presence at a site. The red line denotes the calculated threshold (2.475 mg/L).

Habitat

The QHEI score is based on the available substrate types and quality, instream cover and quality, riparian zone quality, stream drainage area and gradient, pool-run-riffle quality, channel morphology, and riffle quality to produce an overall qualitative score. The substrate, instream cover, and channel morphology scores have a maximum potential of 20 points, the pool-current score has a potential score of 12, riparian quality and gradient metrics have a potential score of 10, and riffle quality has a potential score of 8. Habitat quality was determined at each site during the initial fish sampling event in streams ranging from small headwaters to major rivers using the QHEI. Scores ranged from 29.0 to 91.5 in the Des Plaines River survey areas. The Poisson model shows that Round Goby prefer higher quality habitat ($p=2.00e^{-16}$; Figure 8). Higher numbers were collected at sites with scores between 50-70, where fast flows would be present. Higher quality habitat would also support a more diverse fish assemblage which, as a whole, may out-compete Round Goby for resources.

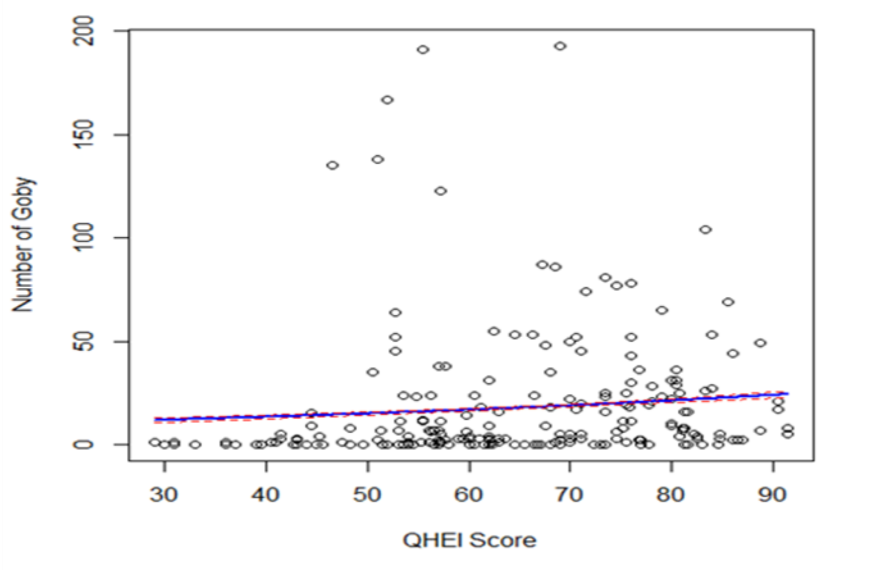

Figure 8. The relationship between the number of Round Goby and the QHEI scores. The blue line represents the logarithmic relationship between Round Goby and habitat score, and the red dashed lines are the 0.95 confidence intervals.

The logistic regression indicates a general increase in the likelihood of Round Goby presence at a site as habitat scores increase (Figure 9a). The derived threshold of 67.12 is considered good for all sites by the Ohio EPA (2006). The ROC curve does not provide confidence that this threshold is appropriate (Appendix A). Fast and very fast flows are generally avoided, and those sites tend to have high QHEI scores. Better habitat conditions increased the likelihood of Round Goby presence at a site. The red line denotes the calculated threshold (67.12). More diverse cover types of higher quality increased the likelihood of Round Goby presence at a site.

The logistic regression shows a sharp increase in Round Goby presence at sites as the cover score increases (Figure 9b). The derived threshold of 15.5 is relatively high in relation to the maximum cover score of 20. Taborelli et al. (2008) identified macrophytes as a preferred cover for Round Goby in Lake Ontario, which was also observed in the Des Plaines River and its tributaries. Aquatic vegetation increases the cover score by both being present and abundant, which is the case through many large- and moderate-sized tributaries.

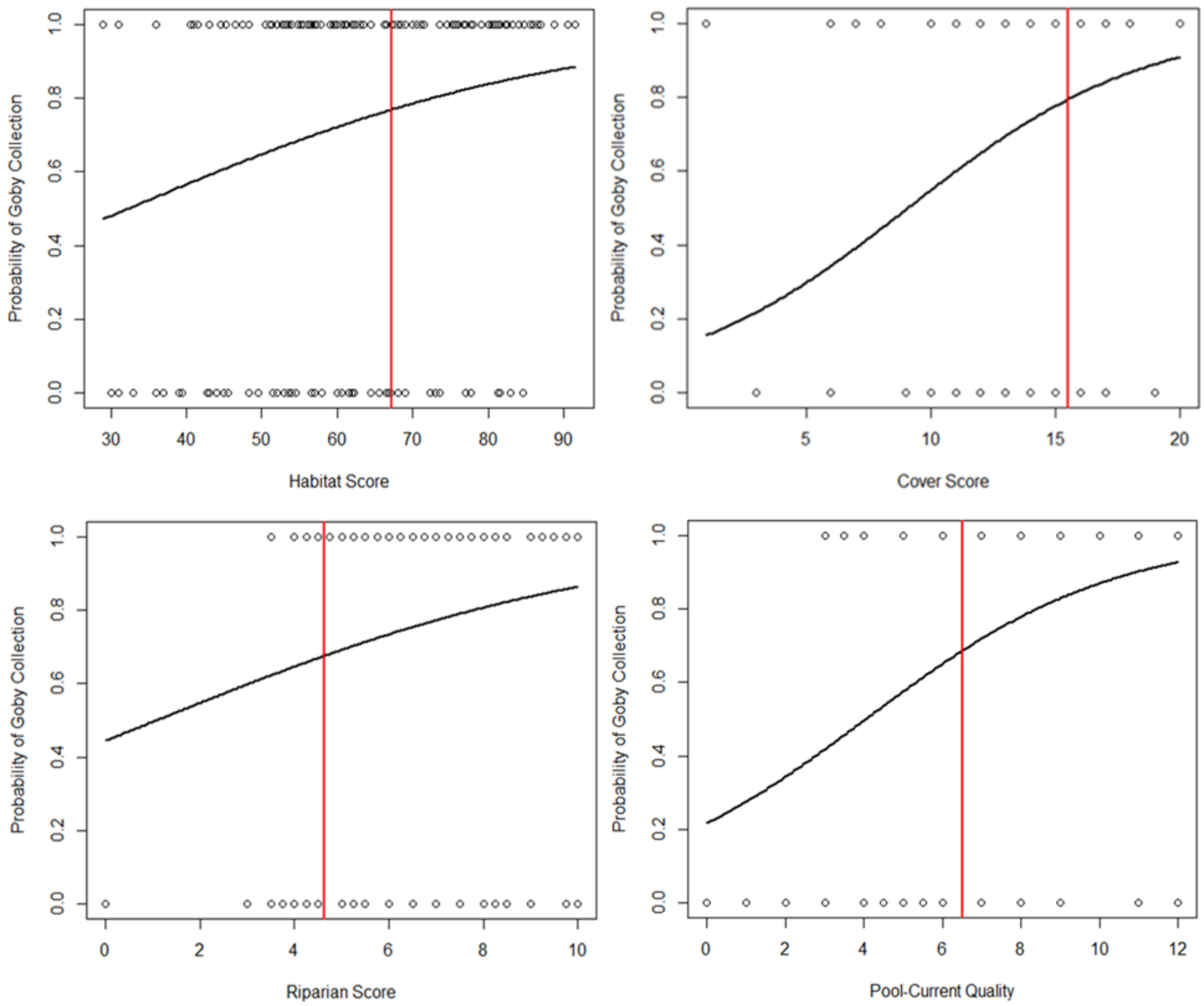

Figure 9. Logistic regression for QHEI score (a), Cover score (b), Riparian score (c), and Pool-Current quality score (d). The red lines denote the respective calculated thresholds.

The logistic regression indicates a sharp increase in the likelihood of Round Goby presence at a site as the riparian score increases. Logistic regression results indicate as riparian scores increase the more likely Round Goby will be present at a site (Figure 9c). The score of 4.625 for the riparian score is low as the metric is scored out of 10, and the ROC curve indicates the threshold may not be accurate (Appendix A). A more robust riparian zone and floodplain increased the likelihood of Round Goby presence at a site.

As with other logistic regression results pertaining to the QHEI metrics, higher pool-current scores result in an increased likelihood of collecting Round Goby at a site (Figure 9d). The pool-current quality score includes maximum pool depth, channel morphology, and current velocity types. The derived threshold of 6.500 is low for a metric in which the maximum score is 12, indicating that high-quality pools, diverse channel morphology, and diverse current types are all not simultaneously required at a site. Higher quality pool and diverse current types increased the likelihood of Round Goby presence at a site.

Conductivity

Specific conductance levels ranged from 592 µS/cm to 2004 µS/cm in the Des Plaines River watershed survey areas. Specific conductance is closely related to total dissolved solids (mg/L; TDS) and chloride (mg/L) concentrations, which in increasing concentrations cause higher specific conductance levels. Round Goby were primarily collected at sites with a specific conductance ranging from 800 µS/cm to 1200 µS/cm, however, 52 individuals were collected at a site with a specific conductance of 2004 µS/cm (Figure 10). The preferred range of specific conductance appears to be between 800 and 1200 µS/cm. The sites with specific conductance above 1500 µS/cm were generally smaller streams with drainage areas below 32 km^2 where a limited number of individuals were collected. The locations above 1500 µS/cm where 50 plus individuals were collected are indicative of Round Goby tolerance of high specific conductance, which is preferred in their native range (Stepien & Tumeo 2006).

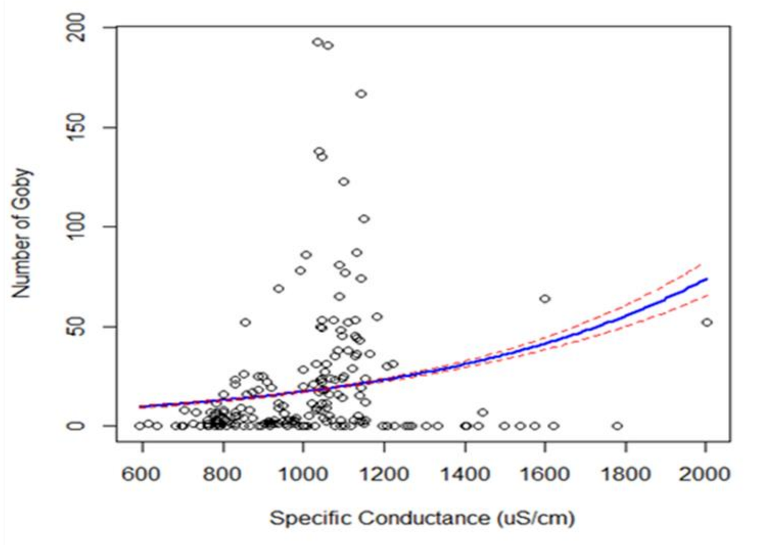

Figure 10. The relationship between the number of Round Goby and the specific conductance in µS/cm. The blue line represents the logarithmic relationship between Round Goby and specific conductance, and the red-dashed lines are the 0.95 confidence intervals.

Total Suspended Solids (TSS)

Total suspended solids (TSS) are particles in the water column that do not dissolve. Median concentrations of TSS ranged from 2.6 mg/L to 88 mg/L in the Des Plaines River watershed. The number of Round Goby collected were significantly ($p=2.00e^{-16}$) affected by TSS and decreased as the concentration of TSS increased (Figure 11). The vast majority of Round Goby were collected when TSS concentrations were below 20 mg/L, with the highest collections occurring at sites with TSS concentrations below 10 mg/L.

The logistic regression results indicate higher TSS concentration reduces the likelihood of Round Goby collection (Figure 12). The derived threshold of 16.25 mg/L is within the range which has deleterious effects on fish assemblages (Troy 2019).

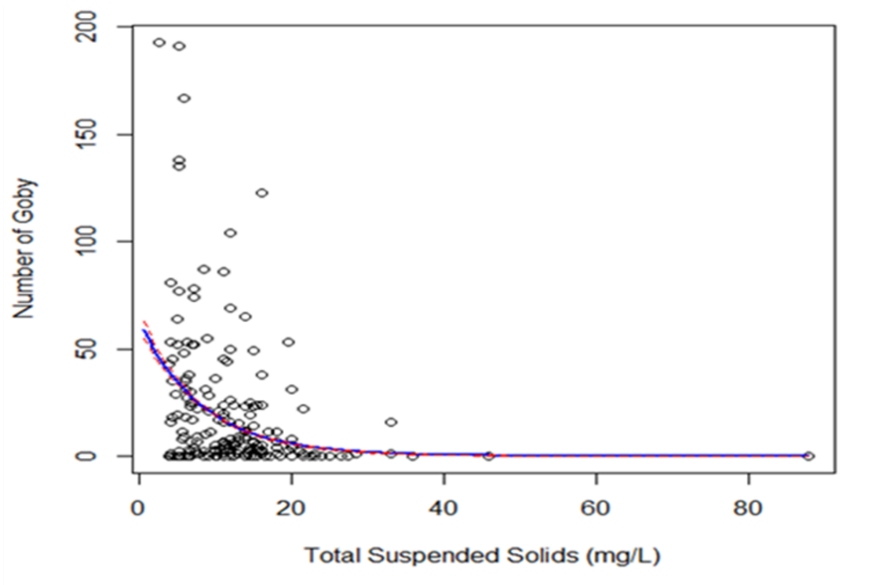

Figure 11. The relationship between the number of Round Goby and the median concentration of TSS. The higher the concentrations of TSS, the fewer Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and TSS concentrations, and the red-dashed lines are the 0.95 confidence intervals.

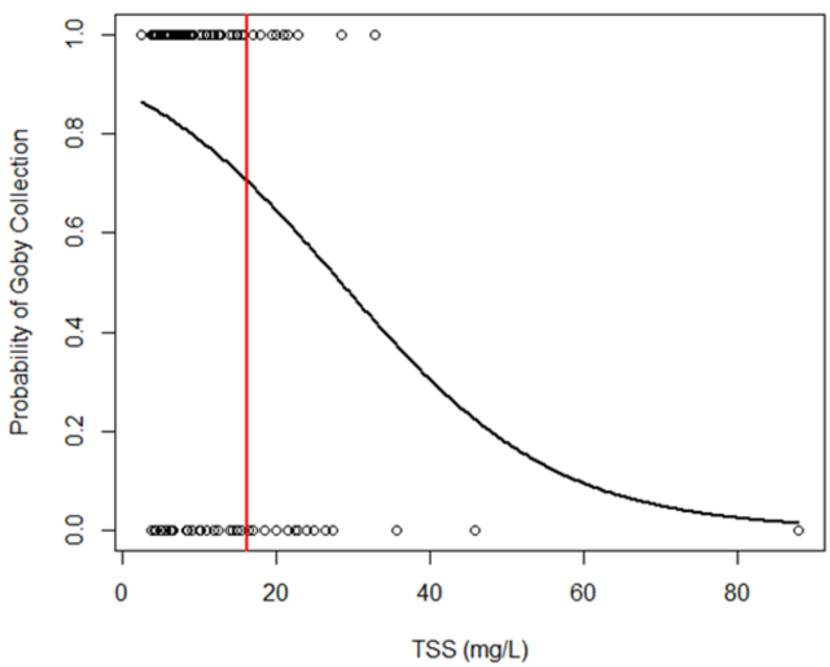

Figure 12. Higher concentrations of TSS decreased the likelihood of Round Goby presence at a site. The red line denotes the calculated threshold (16.25 mg/L).

Total Kjeldahl Nitrogen (TKN)

Median concentrations ranged from 0.2 mg/L to 1.95 mg/L from 2018 to 2021 (Figure 13). Total Kjeldahl nitrogen (TKN) is related to algal growth, which causes increased turbidity, wide D.O. swings, and low D.O. conditions. Round Goby were intolerant to high concentrations of TKN with Goby densities declining as concentrations increased. Ammonia was not found to be a significant factor in Round Goby, which indicates that organically bound nitrogen is the affecting factor. Higher concentrations of sestonic algae may have the same effect as TSS, increasing turbidity and limiting the foraging capability of Round Goby. Higher concentrations of TKN could also be correlated to higher concentrations of benthic algae, when overly abundant, that fill interstitial spaces of course substrates which limit cover and foraging habitat.

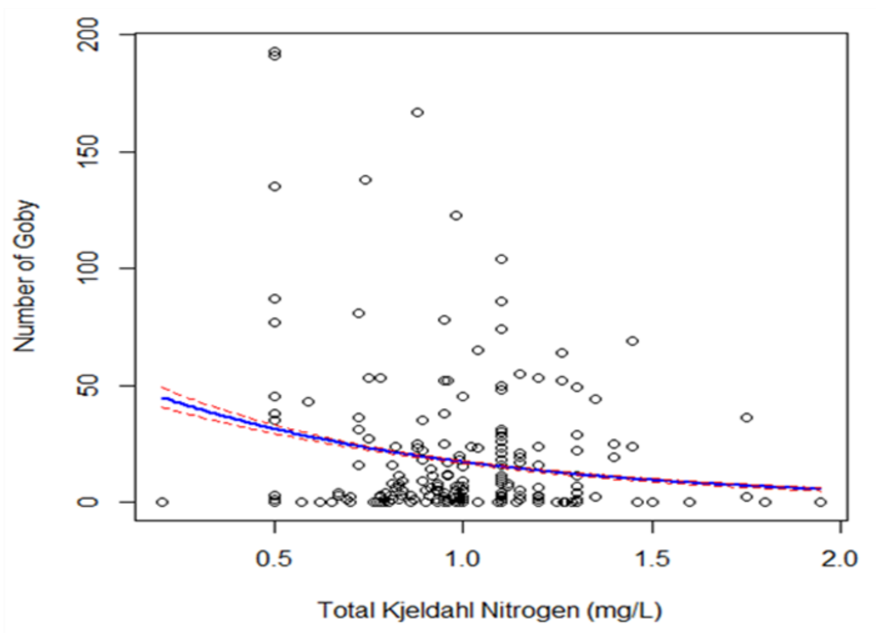

Figure 13. The relationship between the number of Round Goby and the median concentration of TKN. The higher the concentrations of TKN, the fewer Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and TKN concentrations, and the red-dashed lines are the 0.95 confidence intervals.

Temperature (°C)

Water temperature ranged from 14.5 °C to 31 °C in the Des Plaines River watershed from 2016 to 2021 (Figure 14). Round Goby densities were significantly ($p=3.27e^{-14}$) affected by water temperature and decrease with increasing temperatures, with the majority of collections occurring between 15 °C and 25 °C. Temperatures beyond 28 °C affect Round Goby physiological performance and under chronic exposure to temperatures above 30 °C increases mortality rates (Christensen et al. 2021).

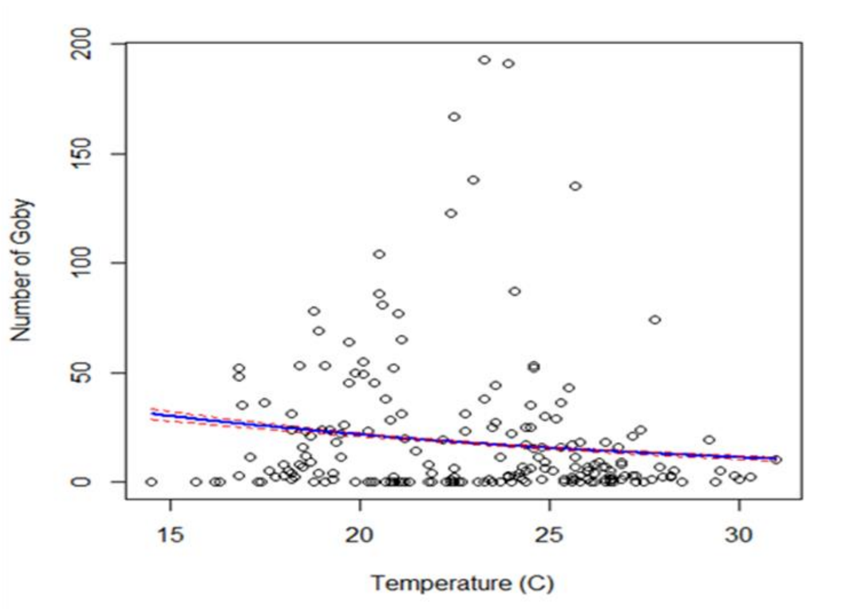

Figure 14. The relationship between the number of Round Goby and water temperature in °C. The higher the temperature, generally, the fewer Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and water temperature, and the red-dashed lines are the 0.95 confidence intervals.

Dissolved Oxygen (D.O.)

Dissolved oxygen (D.O.) concentrations ranged from 2.66 mg/L to 16.13 mg/L in the Des Plaines River watershed from 2016 to 2021. Concentrations above 12 mg/L indicate over-enrichment that causes wide D.O. swings that are detrimental to aquatic life and exclude increased with higher D.O. concentrations, and individuals were collected at sites with sensitive fish species. Round Goby densities were significantly affected (p=2.09e-7) and concentrations above the over-enrichment threshold as well as below 4 mg/L (Figure 15). The logistic regression shows a sharp increase in the likelihood of collecting Round Goby at a site with a threshold of 6.845 mg/L (Figure 17).

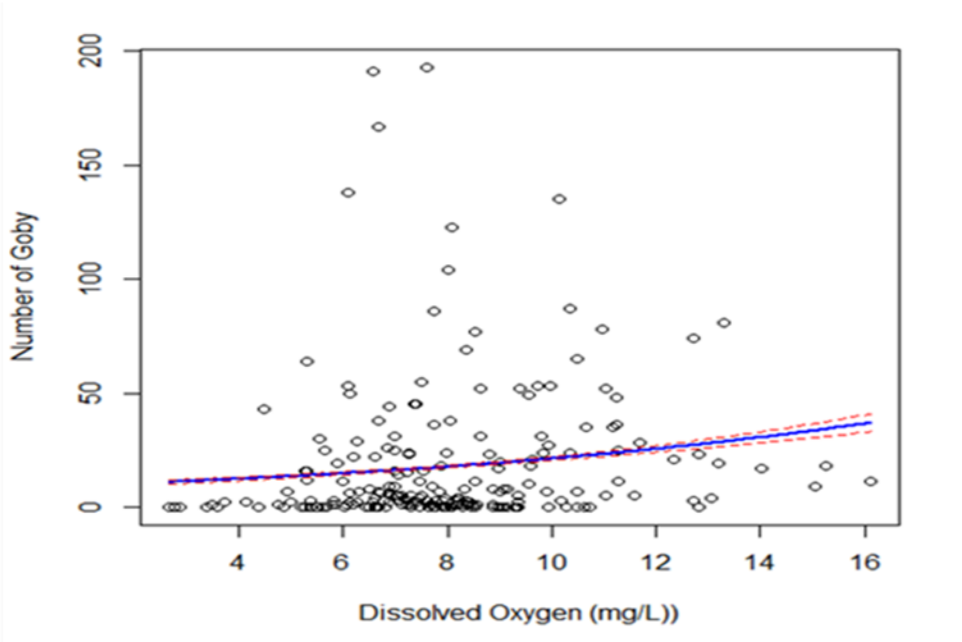

Figure 15. The relationship between the number of Round Goby and D.O. in mg/L. The higher the D.O. concentration, generally, the more Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and water temperature, and the red-dashed lines are the 0.95 confidence intervals.

Ammonia

Median concentrations ranged from 0.05 mg/L to 0.55 mg/L, far below the Illinois chronic toxicity criterion of 1.24 mg/L and the acute toxicity criterion of 8.40 mg/L, both calculated with a pH of 8.0 at a temperature of 25 °C. Within the recorded ammonia concentrations, Round Goby densities were not significantly (p=0.6900) affected in the survey areas.

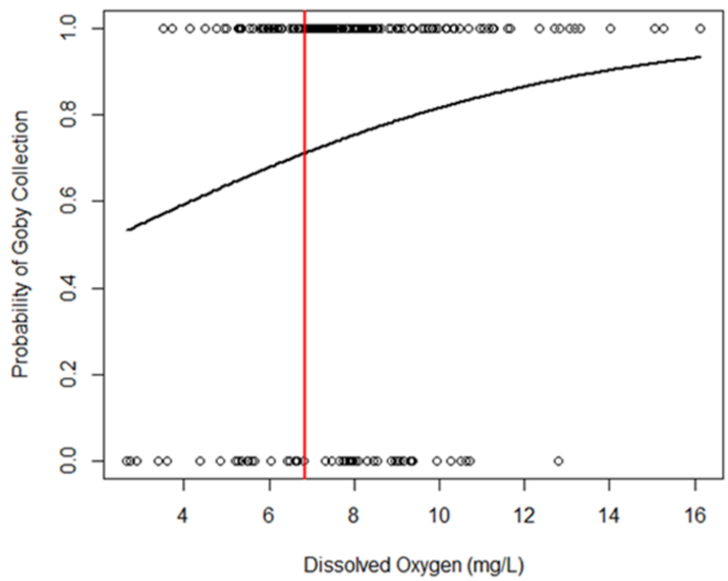

Figure 16. Higher D.O. concentrations decreased the likelihood of Round Goby presence at a site. The red line denotes the calculated threshold (6.845 mg/L).

CHAPTER FOUR

DISCUSSION

The expansion and establishment of Round Goby in the Des Plaines River watershed is unsurprising because the habitat and water quality conditions are nearly ideal for the species. High levels of nitrates provide nutrients to aquatic macrophytes, and limit fish assemblage quality through the exclusion of sensitive species. Moderate to high levels of specific conductance also limit fish assemblages, thus creating less competition for food and cover. Streams are channelized and low gradient with gravel, cobble, and boulder substrates throughout the watershed.

Anthropogenic disturbances to rivers and streams are prevalent throughout the Midwest, affecting fish species and whole assemblages. Fish species tolerant to human impacts generally benefit where sensitive species are hindered or excluded. Round Goby profit from various chemical and physical alterations to lotic systems. Nitrates provide nutrients for the preferred cover of aquatic macrophytes to proliferate in open channels, which are created through channelization, and riparian encroachment and removal. Low D.O. and wide D.O. swings are created by the abundant macrophytes along with algae and highly organic sediments found throughout the watershed. High levels of specific conductance are created through inputs of fertilizers, road salts, WWTP discharges, and industrial wastewater. Each of these factors aid Round Goby populations by either excluding sensitive species or providing an environment in which they thrive. All conditions can be found in areas with high percentages of both urban and agricultural land uses.

Before 2014, there were no observations of Round Goby at any location in MBI survey areas of Des Plaines River tributaries. In 2014, seventeen individuals were collected in the lower East Branch DuPage River during ten sampling events, and in 2015, five individuals were collected below the Channahon Dam during a watershed scale survey of the Lower DuPage River watershed. The Channahon Dam is impassable to the upstream movement for fish, making the remarkable expansion of Round Goby in the DuPage River watershed starting point likely a bait bucket release in the lower East Branch DuPage sometime in 2013 or early 2014, and the origin of individuals collected below the Channahon Dam were from the Des Plaines River. By 2018, the spread included portions of the West Branch DuPage River, East Branch DuPage River, the entire stretch of the Lower DuPage River mainstem, and Lower Lily Cache Creek (Figure 2b).

The Des Plaines River and its tributaries are generally low-gradient, formerly wetland streams that were channelized which altered substrates and flow regimes. Urban and agricultural land uses input nitrogenous compounds, chlorides, and TDS into small streams and major rivers. Rivers and streams throughout the Missouri River, Ohio River, and Mississippi River watersheds are afflicted by similar forms of pollution to varying degrees as the Des Plaines River and tributaries. Medium-sized streams to small rivers that possess clean, coarse substrates, in agricultural or suburban areas where streams are low-gradient, and flows are slow to moderate are most susceptible to Round Goby expansion. Downstream movement can happen quickly with upstream movement relatively slow, so the expectation is that tributaries in the lower Mississippi River would be affected first. These watersheds encompass the bulk of the river miles in the United States with diverse fish assemblages. Perhaps, just as concernting, is the ability of the species to survive in waters with high concentrations of chlorides. Given enough time, direct tributaries to the Gulf of Mexico could also become inhabited.

Efforts to limit the expansion of Round Goby are required in several areas using previously developed techniques. Habitat restoration efforts should include riffle installations that have fast flows and create deep, fast runs and deep pools, riparian corridor restoration where trees are prioritized to provide shade for the stream channel, and connection of the flood plain to remove nutrient-rich sediments during periods of high flows should be prioritized to limit Round Goby populations in degraded systems. Chlorides can be reduced or limited through the use of brine for deicing efforts, WWTP upgrades to include ultraviolet disinfection, and best management practices (BMPs) in agricultural fields. Nutrients can be decreased through restoration efforts, BMPs, and upgrades to WWTPs.

Understanding the impacts of anthropogenic disturbances on lotic systems and their relationship to Round Goby densities is important in understanding where potential areas of colonization and the potential of this species to further its expansion throughout the Mississippi River and Ohio River watersheds is a possibility. Further research needs to be conducted on whole fish assemblages inhabiting the same sites as Round Goby in the Des Plaines River drainage. Previous studies have looked at one or a few native benthic species (Balshine et al. 2005; Bergstrom and Mensinger 2009), a limited number of native species (Morissette et al. 2018), or fish communities studied in lentic systems (Leinoand and Mensinger 2016). All North American studies are located in the Great Lakes, limiting our understanding of how Round Goby will move through the Mississippi and Ohio River watersheds. The Illinois Fish Index of Biotic Integrity (fIBI), a tool for determining impairment causes that include habitat and pollution, will also need to be examined where pre- and post-introduction data exists. So, if Round Goby are unknowingly having a negative effect on fish assemblages it would impair a researcher's ability to determine causal non-attainment of the Illinois General Use designation.

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APPENDICIES

APPENDIX A

ROC CURVE GRAPHS

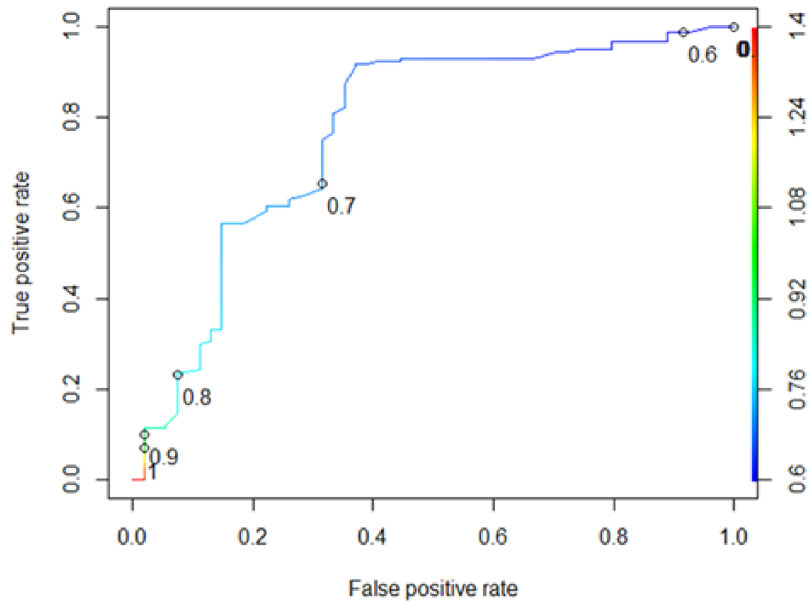

Figure 17. The ROC curve for nitrates in relation to Round Goby presence has an area under the curve (AUC) of 0.7701, indicating that it is 77.0% accurate in differentiating between positive and negative classes.

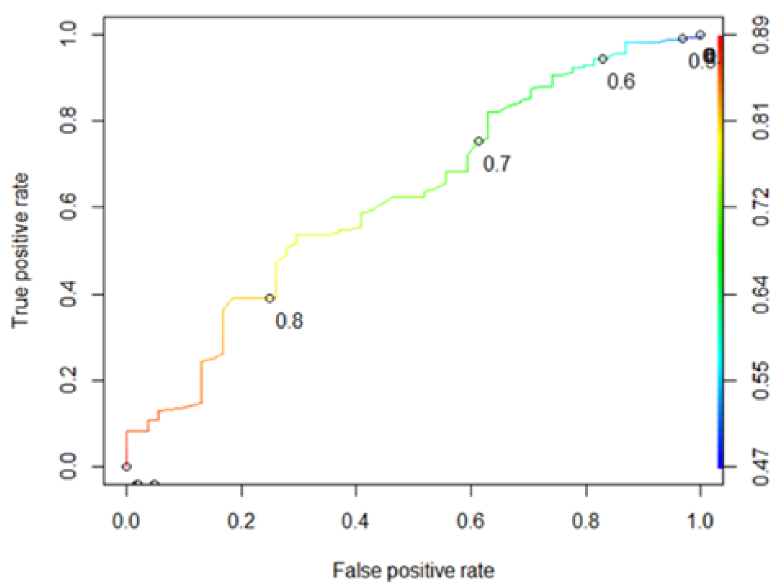

Figure 18. The ROC curve for overall habitat score in relation to Round Goby presence has an AUC of 0.6260, indicating that it is 62.6% accurate in differentiating between positive and negative classes.

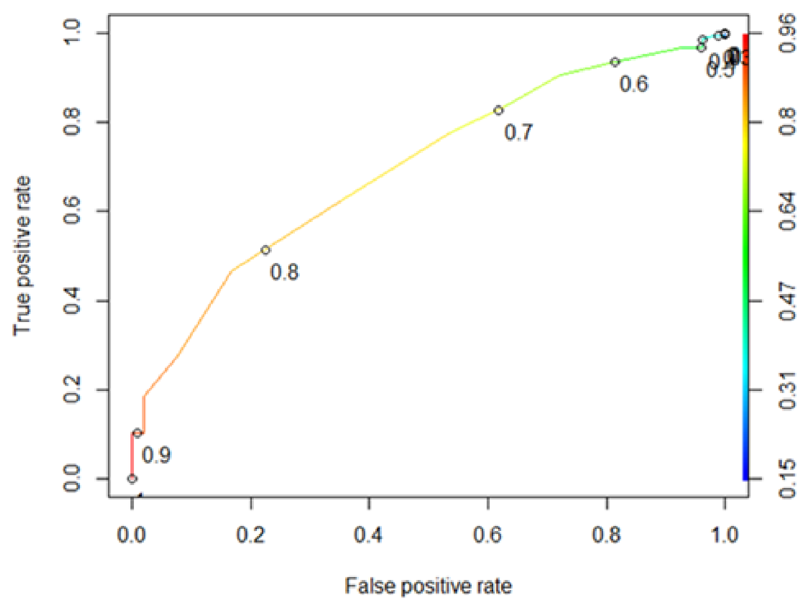

Figure 19. The ROC curve for the cover score in relation to Round Goby presence has an AUC of 0.6982, indicating that it is 69.8% accurate in determining Round Goby presence.

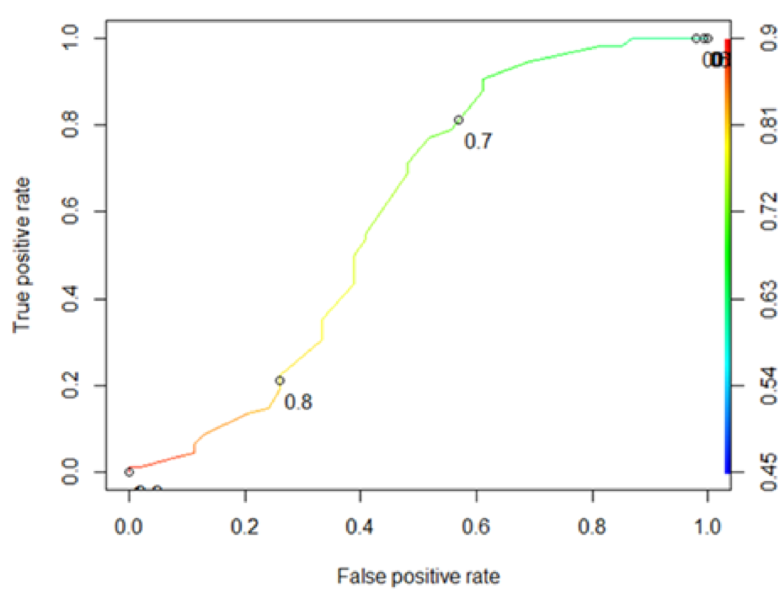

Figure 20. The ROC curve for the riparian score in relation to Round Goby presence has an AUC of 0.5977, indicating that it is 59.8% accurate in determining Round Goby presence.

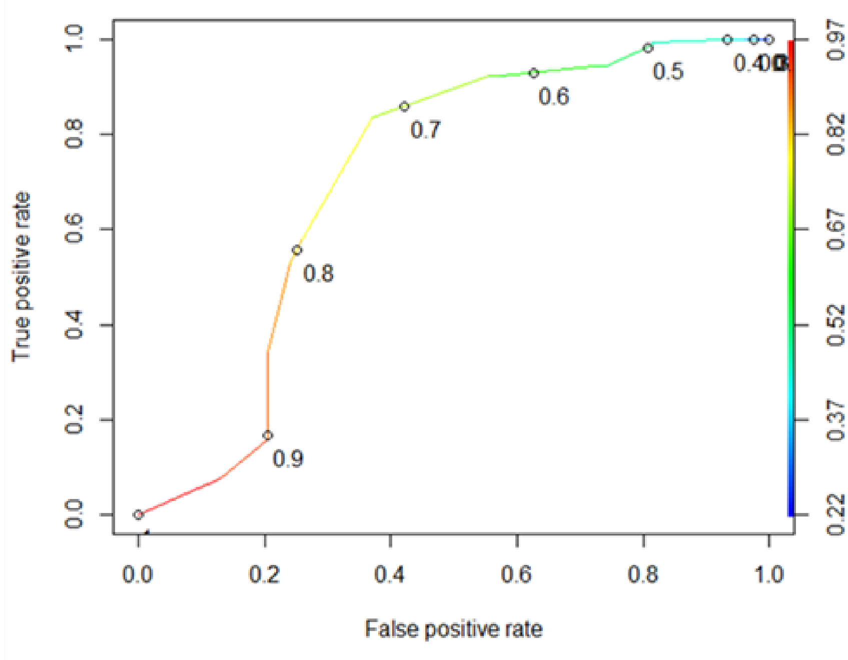

Figure 21. The ROC curve for the pool-current quality score in relation to Round Goby presence has an AUC of 0.7105, indicating that it is 71.1% accurate in determining Round Goby presence.

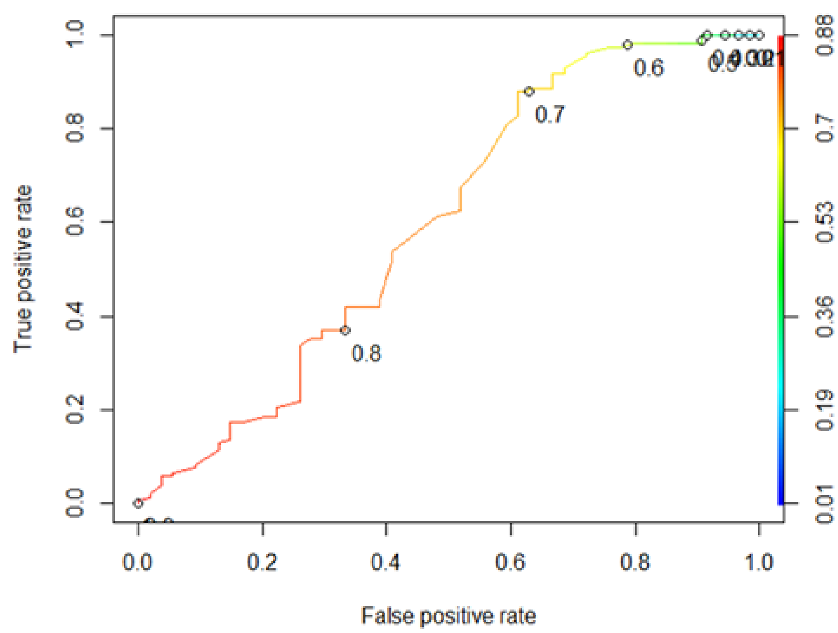

Figure 22. The ROC curve for TSS in relation to Round Goby presence has an AUC of 0.5995, indicating that it is 60% accurate in determining Round Goby presence.

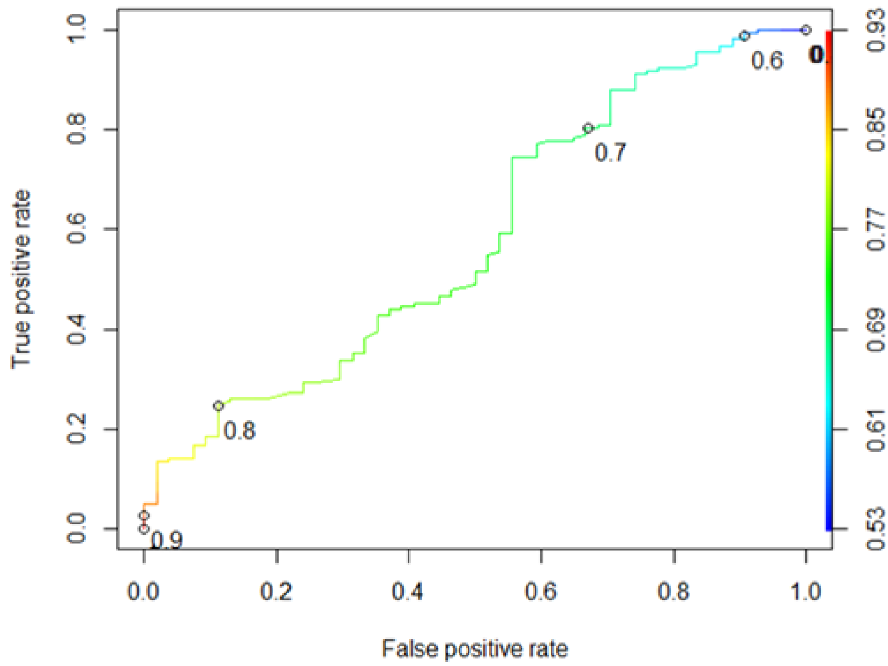

Figure 23. The ROC curve for D.O. in relation to Round Goby presence has an AUC of 0.5807, indicating that it is 58.1% accurate in determining Round Goby presence.