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Round Goby (*Neogobius melanostomus*) Introduction and Range Expansion in the Highly Anthropogenic Influenced Watershed of the Des Plaines River, Illinois, USA

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ABSTRACT

The Round Goby (*Neogobius melanostomus*) is an invasive species of fish 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 highly anthropogenically influenced Des Plaines River and its tributaries beginning in 2014. Densities of Round Goby were compared to habitat conditions and select analytes to determine what factors are fueling colonization and proliferation in these new localities. The selected model indicates habitat conditions, nitrates, conductivity, total Kjeldahl nitrogen (TKN), total suspended solids (TSS), temperature, and dissolved oxygen (D.O.) are 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 are tolerated by Round Goby.
Keywords: Invasive species, Round Goby, Water Quality

INTRODUCTION

Foreign species have been introduced throughout North America having deleterious impacts on aquatic and terrestrial ecosystems and economies. Agriculture, silviculture, and fisheries have been negatively affected by the introduction of invasive species. The mechanisms of invasive species expansion into new ecosystems occur via various processes, including purposeful or accidental introduction, and movement through natural modes. Non-native fishes 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). Introductions of invasive fishes into the Upper Mississippi River watershed from the Great Lakes and vice versa have been facilitated by the Chicago Sanitary and Ship Canal. Construction of the Canal was completed in 1900 as a method of diverting pollution away from Lake Michigan and allowing for trade to be conducted from the Lake to the interior of Illinois. The connection to the Des Plaines River was finished in 1907, providing a mode of passage for ships and organisms from Lake Michigan to the upper Mississippi River watershed.

Round Gobies (*Neogobius melanostomus*) are a benthic species native to the Caspian and Black Seas and have been introduced across Europe and the United States. The expansion of this species has been likely facilitated by international trade through the shipping of goods (Roche et al. 2015; Marsden and Jude 1995; Rice and Zimmerman 2019; Figure 1). 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, many of their tributaries, and even in the Illinois River watershed. Initially observed in 2003 by the United States Fish and Wildlife Service (US FWS) in the Des Plaines River, the Illinois Natural History Survey (INHS) expanded the known range into the middle Illinois River in 2004 (Irons et al. 2006). Introduction to the Des Plaines River occurred through the movement of both ships and individuals moving through the Chicago Sanitary and Ship Canal. Further observations have been made in the Des Plaines River mainstem and its tributaries with extensive records being observed in major tributaries such as the DuPage River and Salt Creek (MBI unpublished).

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.

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 where flows are moderate, and stream gradients are low to moderate (Ray and Corkum 2001; Brownscombe and Fox 2012; Reid 2019). 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 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.

Human impacts have occurred in the Des Plaines River watershed through the centuries. Organic, poorly drained soils that once dominated the region have been drained for agriculture and paved over for urban land uses. Over that period, the mainstem and tributaries have been channelized and incised. Prior to the expansion of Chicago, The River would discharge a small volume of water. Historically the Des Plaines River contained little in terms of volume of water flowing within its banks and would become ephemeral during dry years. As Chicago expanded, the discharge increased from a median of fewer than 10 cfs before World War II to a median discharge of 881 cfs in 2020 (Greenberg 2002). Wastewater treatment plants (WWTP) have also been built to service the greater Chicago area residents to treat and lessen the impacts of various pollutants in the watershed. The number of WWTPs in production causes the upper watershed of the Des Plaines River to be an effluent-dominated system (MBI 2020). WWTPs also alter the base flow of the Des Plaines River by providing a continuous discharge during dry periods. The dramatic changes in land use, altered channels of tributaries and the Des Plaines River, and wastewater introduction have influenced the habitat and flow regimes.

Effluent from WWTPs alters the chemical composition of lotic systems in addition to increasing base flows. Treated wastewater contains various nutrient pollutants including ammonia-N and nitrate-N, which can significantly affect D.O. and pH values. In high enough concentrations, nutrients facilitate the excessive growth of nuisance algae. Diel patterns of photosynthesis and respiration cause extreme high and low pH values and wide swings in the same manner that D.O. concentrations can be extremely high during daylight hours and fall to levels that cannot support diverse aquatic life assemblages. In addition to nutrients, other pollutants such as dissolved solids (TDS), suspended solids (TSS), and chlorides are discharged in treated wastewater. Each pollutant is deleterious to fish assemblages and locally excludes intolerant species when elevated concentrations are imported into the receiving system (Pokharel et al. 2018; Hued et al. 2010; MBI 2020).

Non-point source pollution from urban and agricultural land uses also input nutrients, chlorides, and other pollutants through surface runoff. Rainwater washing off impervious surfaces, lawns, and farm fields Rainwater washes pollutants into neighboring streams through tiling and stormwater sewers. The cities of Chicago, Joliet, and their suburbs all line the banks of the Des Plaines River mainstem and have numerous tributaries flowing through their boundaries that receive the bulk of the runoff, exporting it via their channels to the Des Plaines. Additionally, the headwaters of the Des Plaines River lay within an agricultural region in southern Wisconsin. Surface runoff from rain events inputs chlorides and TDS via road salts, and nitrogen, TDS, and chlorides from urban and agricultural sources.

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 the Midwest Biodiversity Institute (MBI). 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 with effluent-dominated systems and the range in degree of modification for anthropogenic uses has not yet been fully studied. Siltation, channelization, water temperature, nutrient and organic enrichment, dissolved oxygen, pH, and chlorides influences are continuous problems 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 whether or not to what degree they facilitate the expansion and colonization of the species. The Round Goby populations of the Des Plaines River provide an opportunity to fill in the knowledge gap of what analytes and habitat conditions provide preferable environmental conditions for this invasive species.

METHODS

Study Area. The Des Plaines River originates in southern Wisconsin, flowing 133 miles south through Chicago before turning southwest toward its confluence with the Kankakee River near Channahon, IL. More than 2000 sq mi 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 (Figure 2). Urban, industrial, agriculture, suburban, park, wetland, and forest account for the majority of the land use in the watershed. Free-flowing for nearly 115 mi from its headwaters to the confluence with the Chicago Sanitary and Ship Canal, the final 16 miles are heavily influenced by

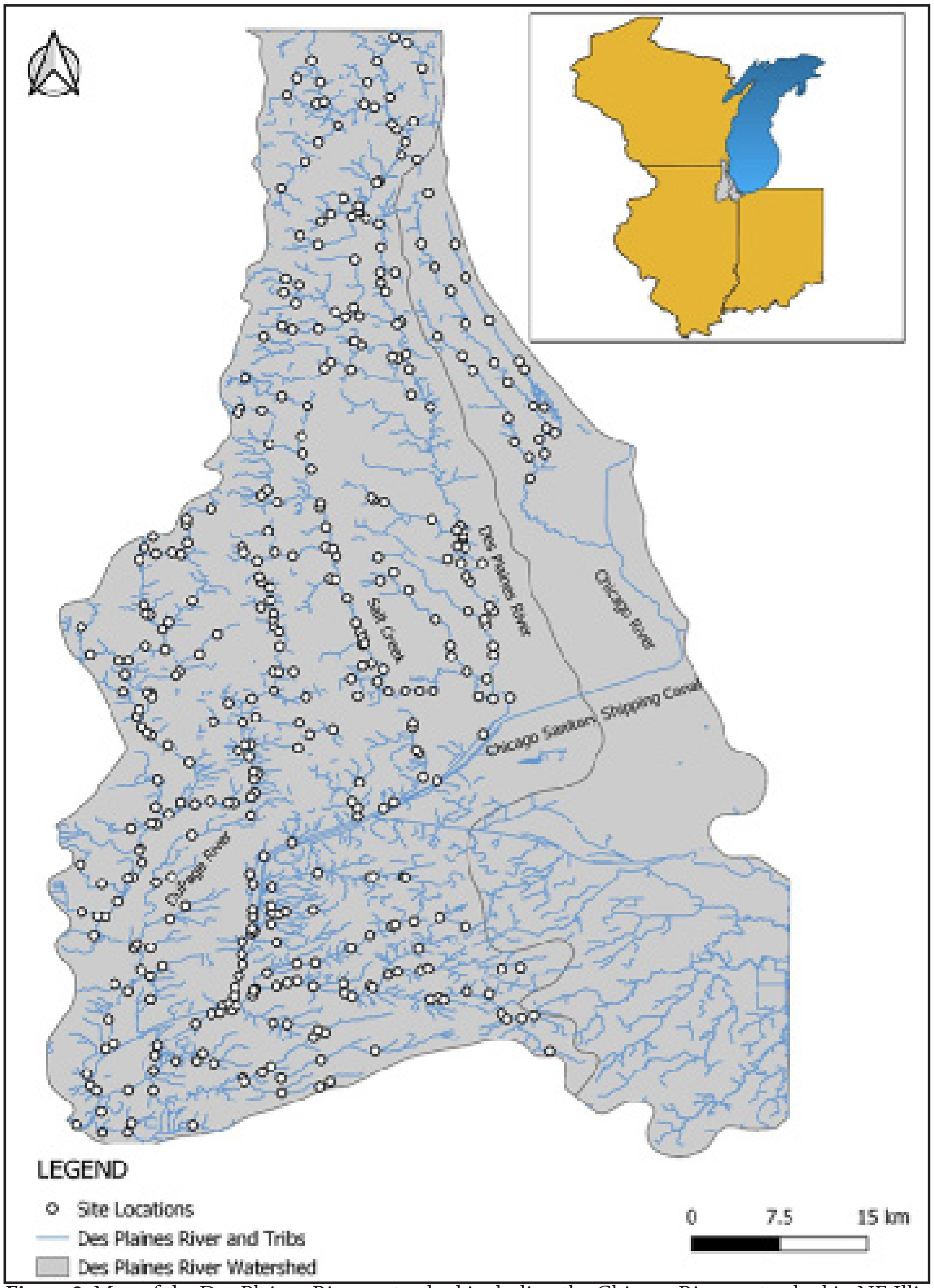

Figure 2. Map of the Des Plaines River watershed including the Chicago River watershed in NE Illinois. Rivers and streams are depicted as blue lines, sites sampled for fish and water chemistry by MBI from 2016-2021 are denoted as white dots and watershed boundaries are dark gray lines.

the Brandon Locks and Dam in Joliet, IL as well the Dresden Locks and Dam on the Illinois River. Fish, habitat, and water chemistry were sampled from 2016 through 2021 at more than 400 locations.

Fish Collection. Fish were collected using pulsed DC electric current. Headwater sites (<20 mi.^{2} drainage area) were sampled at a distance of 0.15 km in an upstream direction using a bank-set longline electrofishing configuration powered by a 5.5 HP generator with a 2500-Watt alternator and a 2.5 GPP Smith-Root control box or a Wisconsin AbP-3 battery-powered backpack electrofishing unit. Wading sites (>20 mi.^{2} drainage area) were sampled at a distance of 0.20 km in an upstream direction using a tote-barge powered by a 5.5 HP with a 2500-Watt alternator and a 2.5 GPP Smith-Root control box. Large river sites 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 electric current was achieved through a Smith-Root 5.0 GPP control box powered by a 11.0 HP generator with a 5000-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. 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 Assessment. The habitat at each site was evaluated using the Qualitative Habitat Evaluation Index (QHEI; Rankin 1989; Ohio EPA 2006). The QHEI is divided into seven (7) 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 Collection. Water chemistry was collected by each watershed group at the same predetermined sites where fish collection occurred. Surface water chemistry collection followed Illinois EPA protocols (2012), and 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 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 Analysis. This data analysis aimed to determine which analytes and habitat conditions are 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.

A correlation plot was created to analyze the relationship between the independent variables and the number of Round Goby.

The variation of inflation factor (VIF) was tested on a saturated model to avoid skewed or misleading results from the standardized independent variables in the car package in RStudio.

No Collinearity 0 < VIF < 2

Collinearity 2 < VIF

The Poisson distribution was selected to analyze the relationship between analytes and habitat conditions to the number of Round Goby at a location.

$$\textbf{Log}(\lambda i) = \beta_0 + \beta_1 x_{i1} + ... + \beta_n x_n$$

Where:

Log(λi) = log of mean number of Round Goby

β_0 = model intercept

B_j = coefficient of independent variable

x_i = predictor variable

A list of 31 generalized linear models (GLMs) using the Poisson method was formulated to test the best fitting model for ascertaining the reasonings 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:

AIC = -2*log-likelihood + k*npar

Where:

AIC = Akaike's Information Criterion

k = number of independent variables

npar = number of parameters in the fitted model

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

RESULTS

Statistical Analysis. This data analysis aimed to determinThe correlation between the number of Round Goby, habitat quality, and analytes is depicted in Figure 3. The highest correlations between the number of Round Goby were conductivity (0.21), 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 an 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 D.O.).

The models tested and the k, AIC, AICc, d.AICc, w.AICc, and evidence rating values are recorded in Table 1. The lowest AICc is associated with the model which fits the true data that possesses the fewest variables (Acquah 2009). The most appropriate model had an AIC of 5702.838, and an AICc of 5719.201.

N = QHEI + TSS + Nitrates + DO + TKN + Temp + Ammonia + Conductivity

Where:

N = number of Round Goby at a location

QHEI = overall qualitative habitat evaluation index score for a sample

TSS = TSS concentration (mg/L)

Nitrates = nitrates concentration (mg/L)

DO = dissolved oxygen concentration (mg/L)

Conductivity = specific conductance (μS/cm)

Ammonia = ammonia concentration (mg/L)

Temp = water temperature (°C)

TKN = total Kjeldahl nitrogen concentration (mg/L)

The VIF values for the saturated models contained multiple variables with collinearity above two (Table 2). This could potentially lead to performance issues with the model, so TDS, pH, and Chlorides were removed from the saturated model.

The VIF values for each variable in the selected model fall below the exclusion

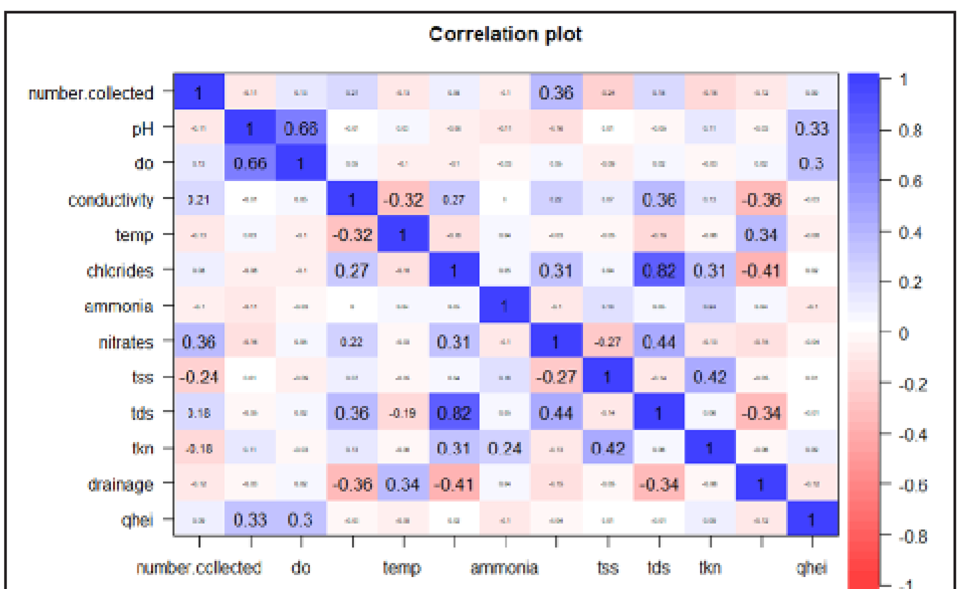

Figure 3. Correlation plot between the number of Round Goby collected, habitat quality, and select analytes. Blue rectangles indicate a positive relationship, and red rectangles indicate a negative relationship.

Table 1. 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	dAICC	w.AICC	evid.rat
1	qhei + tss + tkn + ammonia + conductivity + temp + nitrates + do	9	5702.838	5719.201	0	0.948084	1
2	qhei + drainage + tss + tkn + ammonia + conductivity + temp + nitrates + do	10	5704.397	5726.397	7.195919	0.025958	36.52363579
3	qhei + drainage + tkn + tss + ammonia + nitrates + conductivity – do + temp	10	5704.397	5726.397	7.195919	0.025958	36.52363579
4	drainage + qhei + tss + ammonia + conductivity + do + temp + nitrates	9	5780.473	5796.837	77.63586	1.31E-17	7.21793E+16
5	qhei + drainage + tss + nitrates + tkn * do	8	5874.388	5886.388	167.1873	4.71E-37	2.01E+36
6	qhei + drainage + tss + nitrates + tkn * do	9	5874.388	5886.388	167.1873	4.71E-37	2.01E+36
7	qhei + drainage + tss + nitrates + tkn * do	8	5874.388	5886.388	167.1873	4.71E-37	2.01E+36
8	tss + tkn + ammonia + conductivity + temp + nitrates + do	8	5901.458	5913.458	194.2564	6.22E-43	1.52E+42
9	drainage + tss + tkn = ammonia + conductivity + temp + nitrates + do	9	5900.271	5916.635	197.4334	1.27E-43	7.45E+42
10	qhei + tss + tkn + nitrates + do	6	5913.562	5919.562	200.3604	2.95E-44	3.22E+43
11	qhei + drainage + tss + nitrates + do	6	5920.344	5926.344	207.1428	9.92E-46	9.56E+44
12	qhei + nitrates + tss – tkn	5	5949.891	5953.891	234.6896	1.03E-51	9.17E+50
13	qhei + tss + nitrates – do	5	5950.825	5964.825	235.6243	6.48E-52	1.46E+51
14	qhei + tss + nitrates – do	5	5950.825	5964.825	235.6243	6.48E-52	1.46E+51
15	qhei + do + nitrates + tss	5	5950.825	5964.825	235.6243	6.48E-52	1.46E+51
16	qhei + tss + nitrates – do	5	5950.825	5964.825	235.6243	6.48E-52	1.46E+51
17	qhei + nitrates + tss	4	5986.79	5989.29	270.089	2.13E-59	4.46E+58
18	tss + ammonia + conductivity + nitrates + do	6	6033.822	6039.822	320.6208	2.26E-70	4.19E+69
19	drainage + tss + nitrates + tkn + do	6	6049.342	6055.342	336.1407	9.66E-74	9.82E+72
20	drainage + tss + nitrates + tkn + do	6	6049.342	6055.342	336.1407	9.66E-74	9.82E+72
21	drainage + tss + nitrates + do	5	6068.091	6072.091	352.8896	2.23E-77	4.25E+76
22	tss + do + nitrates + drainage	5	6068.091	6072.091	352.8896	2.23E-77	4.25E+76
23	tss + tkn + nitrates + do	5	6091.814	6095.814	376.6124	1.57E-82	6.03E+81
24	tss + tkn + nitrates + do	5	6091.814	6095.814	376.6124	1.57E-82	6.03E+81
25	tss + do + nitrates	4	6112.122	6114.622	395.4211	1.29E-86	7.32E+85
26	drainage + nitrates + tss	4	6160.209	6162.709	443.508	4.68E-97	2.03E+96
27	qhei + nitrates	3	6932.445	6933.858	1214.657	1.65E-264	5.75E+263
28	qhei + tkn + ammonia + conductivity + temp	6	7147.287	7153.287	1434.085	3.7082312	Inf
29	1	1	8311.481	8311.691	2592.49	0	Inf
30	qhei	2	8213.961	8214.627	2495.426	0	Inf

Table 2. 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
1.338295	1.452877	1.347797	2.271014	2.800987	2.098978	1.25841	2.014726	1.290638	6.091584	6.250988	3.705956

Table 3. 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
1.281599	1.272278	1.242327	1.335213	1.101454	1.109736	1.599985	1.124299

Table 4. 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				

threshold of 2, indicating all independent variables are acceptable for the model (Table 3).

The dispersion parameter value of 1 is near the ideal σ. This indicates low fluctuation around the mean of the data. The model is significant (p-value < 2.00e^{-16}) in determining the number of Round Goby at a site (Table 4). Seven (7) of the eight (8) independent variables were significant in the model (p<0.05; Table 4). 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}), and conductivity (p-value < 2.00e^{-16}). Followed by 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.

Round Goby Abundance. A total of 5261 Round Goby individuals were collected at a total of 211 sampling events in the Des Plaines River watershed. Small river sites were the most numerous (n=143), followed by headwater (n=42), wading (n=38), and large river (n=12; Figure 4). A total of 2925 individuals were collected at small river sites from 2016 to 2021 (20.5 individuals/sample), 2089 individuals at 226 headwater sites (5.4 individuals/sample), 2089 individuals at wading sites (55.0 individuals/sample), and 21 individuals during large river samples (1.8 individuals/sample).

Water Chemistry.

Nitrates. In the Des Plaines River watershed, median nitrate concentrations ranged from 0.160 mg/L to 19.0 mg/L. Round Goby densities were significantly affected by nitrate concentrations (p=2.00e^{-16}), where higher concentrations of nitrates supported higher numbers of Round Goby (Figure 5).

Total Kjeldahl Nitrogen (TKN). Median concentrations of Total Kjeldahl nitrogen (TKN) ranged from 0.2 mg/L to 1.95 mg/L from 2016 to 2021. Round Goby densities were significantly (p=2.00e^{-16}) affected by TKN and declined in numbers with increasing TKN concentrations (Figure 6).

Specific Conductance. Specific conductance levels ranged from 592 μS/cm to 2004 μS/cm in the Des Plaines River watershed survey areas. 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 7). Densities were significantly higher (p=2.00e^{-16}) at sites with higher conductivity levels.

Total Suspended Solids (TSS). 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 8). The vast majority of Round Goby were collected when TSS concentrations were below 20 mg/L, with the highest collections oc-

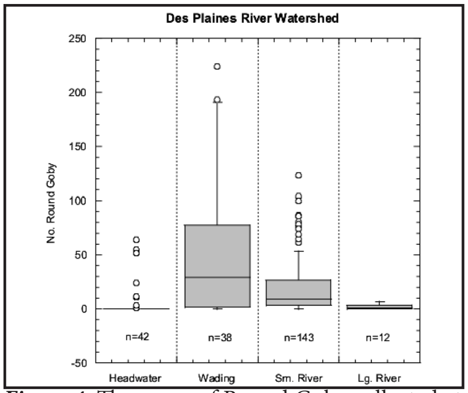

Figure 4. The range of Round Goby collected at headwater, wading, small river, and large river sites. The number of samples in each category is listed below each plot.

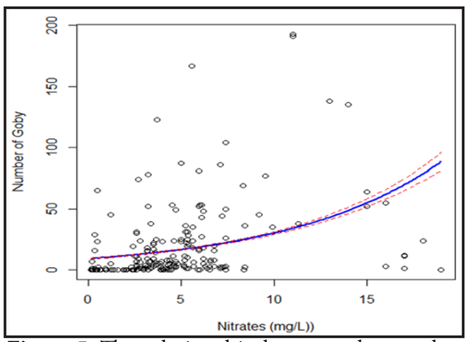

Figure 5. The relationship between the number of Round Goby and the median concentration of nitrates. The higher the concentrations of nitrates, the more Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and nitrate concentrations, and the red-dashed lines are the 0.95 confidence intervals.

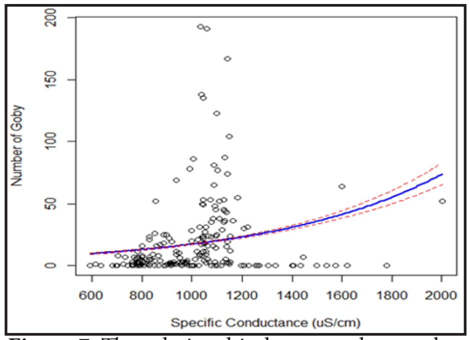

Figure 7. The relationship between the number of Round Goby and the specific conductance in µS/cm. The higher the specific conductance of a site, the more Round Goby individuals observed. The blue line represents the logarithmic relationship between Round Goby and specific conductance, and the red-dashed lines are the 0.95 confidence intervals.

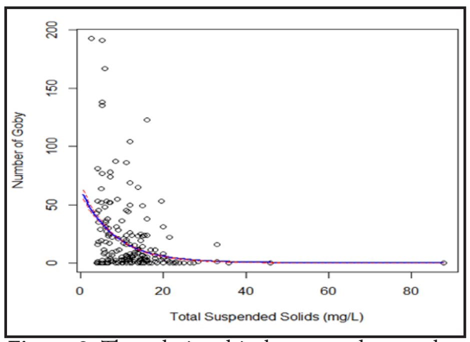

Figure 8. The relationship between the number of Round Goby and the median concentration of TSS. The higher the concentrations of TSS, the fewer Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and TSS concentrations, and the red-dashed lines are the 0.95 confidence intervals.

curring at sites with TSS concentrations below 10 mg/L.

Temperature. Water temperature ranged from 14.5 °C to 31 °C in the Des Plaines River watershed from 2016 to 2021. Round Goby densities were significantly ($p=3.27e^{-14}$) affected by water temperature decreasing with increasing temperatures, with the majority of collections occurring between 15 °C and 25 °C (Figure 9).

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. Round Goby densities were significantly affected ($p=2.09e^{-7}$) and increased with higher D.O. concentrations, and individuals were collected at sites with concentrations above the over-enrichment threshold as well as below 4 mg/L (Figure 10).

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.

Habitat. Habitat quality was determined at each site during the initial

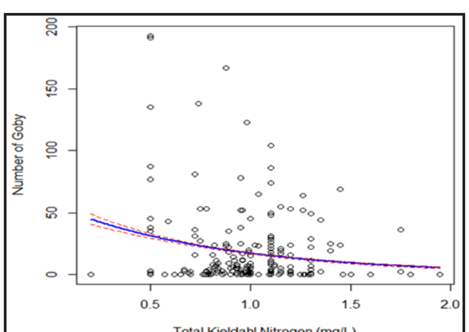

Figure 6. The relationship between the number of Round Goby and the median concentration of TKN. The higher the concentrations of TKN, the fewer Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and TKN concentrations, and the red-dashed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

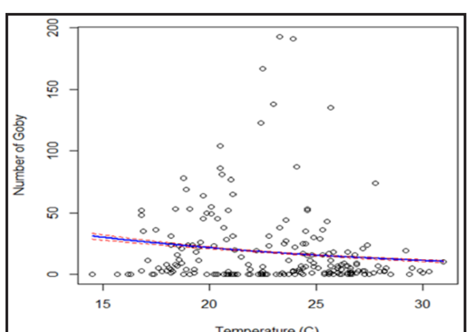

Figure 9. The relationship between the number of Round Goby and water temperature in °C. The higher the temperature, generally, the fewer Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and water temperature, and the red-dashed lines are the 0.95 confidence intervals.

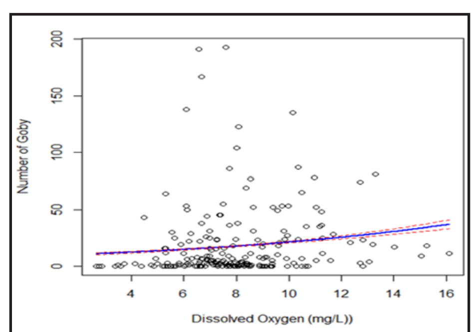

Figure 10. The relationship between the number of Round Goby and D.O. in mg/L. The higher the D.O. concentration, generally, the more Round Goby individuals observed at a site. The blue line represents the logarithmic relationship between Round Goby and water temperature, and the red-dashed lines are the 0.95 confidence intervals.

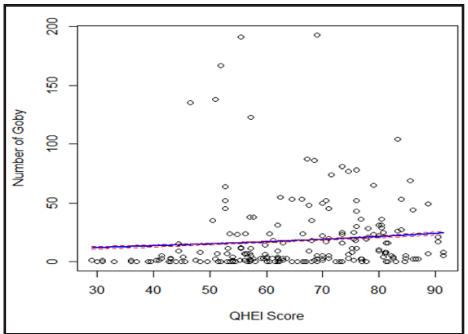

Figure 11. The relationship between the number of Round Goby and the QHEI scores. The better the habitat score the more Round Goby observed at a site. The blue line represents the logarithmic relationship between Round Goby and habitat score, and the red dashed lines are the 0.95 confidence intervals.

fish sampling event in streams ranging from small headwaters to major rivers using the QHEI. 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 sequence 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, pool-run-riffle sequence has a potential score of 12, the riparian quality and gradient scores have a potential score of 10, and riffle quality has a potential score of 8 totaling a maximum score of 100. Scores ranged from 29.0 to 91.5 in the Des Plaines River survey areas. Round Goby prefer sites with overall higher quality habitat ($p=2.00e^{-16}$; Figure 11).

DISCUSSION

Before 2014, there were no observations of Round Goby at any location in MBI survey areas of Des Plaines River tributaries. In 2014, 17 individuals were collected in the lower East Branch DuPage River during 10 sampling events, and in 2015, 5 individuals were collected below the Channahon Dam during a watershed scale survey of the Lower DuPage River watershed. The Channahon Dam is impassable to 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 moved the Des Plaines River. By 2018, the downstream 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.

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. A total of Round Goby were collected at 92 sites during 194 sampling events between 2016 and 2021 in the Des Plaines River drainage (Figure 12). A 2019 survey of the East Branch DuPage River yielded 945 individuals at 11 locations, with further observa-

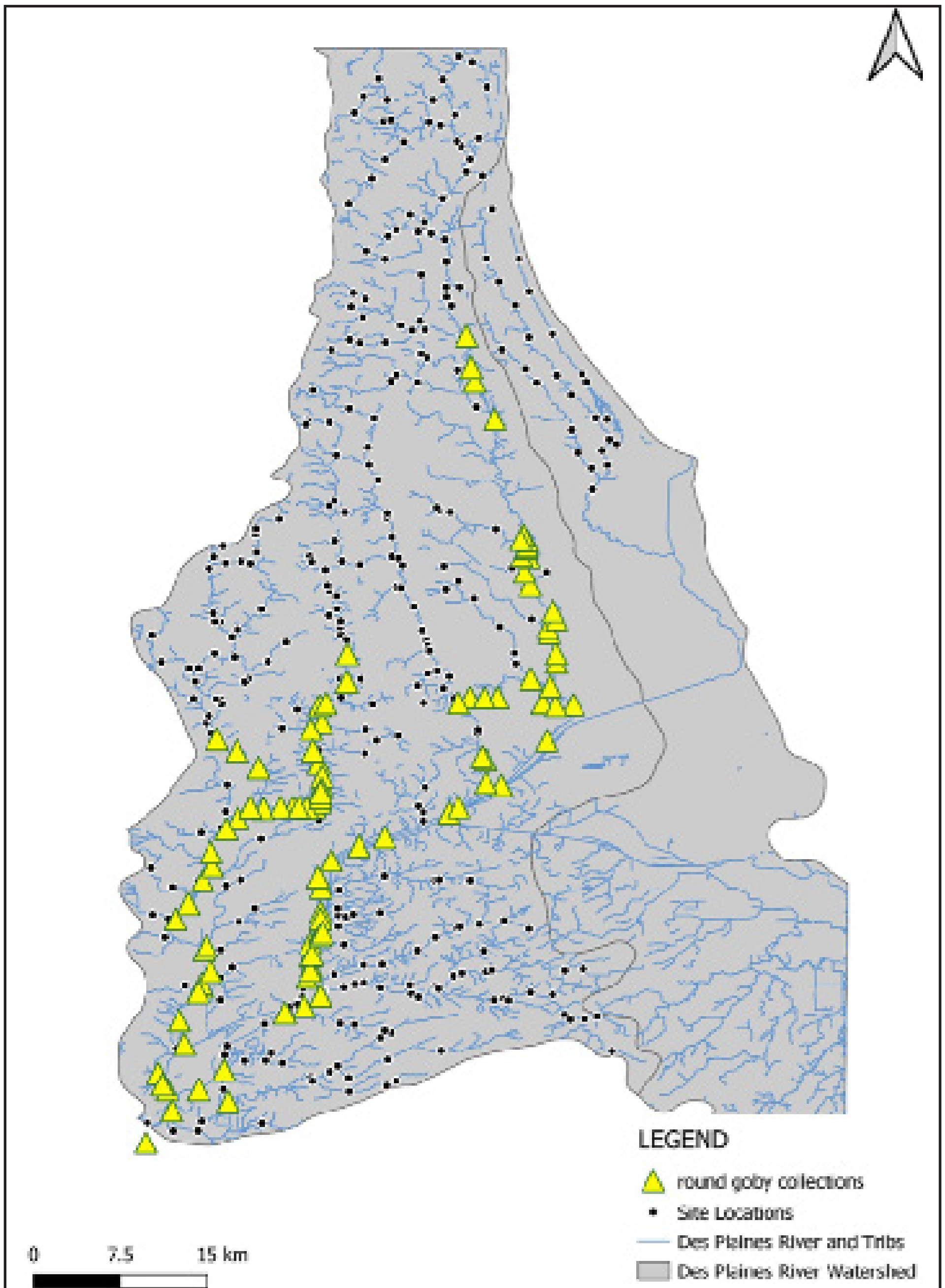

Figure 12. Round Goby collections from 2016-2021 (yellow triangles) in the Des Plaines River watershed in relation to MBI site locations (black dots).

tions in the West Branch DuPage River in 2020 up to the Falwell Dam. Slow upstream movement in the Des Plaines River has reached Lake County, with 21 individuals collected at 4 locations. These expansions have been facilitated by favorable habitat conditions, high nitrates, the ability of the species to adapt to low D.O. concentrations and wide diel swings, and high conductivity levels despite TKN and TSS being limiting analytes.

Water Chemistry.

Nitrogen. Nitrogen-based analytes are input to the Des Plaines River and tributaries through both point- and non-point- source pollution. Treated wastewater inputs nitrates during the process of removing ammonia from effluent. Nitrates are also used in fertilizers on agricultural fields in the headwaters of the watershed. Nitrates and other nutrients contribute to chlorophyll production, which has a direct impact on D.O. concentrations. Physiological alterations, hypoxia, and death in fish are potential causes of high concentrations of nitrates (Gomez-Isaza 2021). Round Goby were generally tolerant to high concentrations of Nitrates, with more than 50 individuals collected at sites containing nitrate concentrations greater than 15 m/L in multiple samples. Round Goby tolerance to high concentrations of nitrates is problematic for the region as agricultural runoff from the upper Des Plaines River watershed is prevalent, and few WWTPs have advanced treatment methods to reduce nitrates from wastewater.

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.

Specific Conductance. 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. Chlorides and TDS are introduced to the Des Plaines River watershed through deicing efforts in the winter, treated wastewater from WWTP, and agricultural runoff. Fish assemblage quality declines with increased chloride and TDS concentrations (Kimmel and Argent 2009; Morgan II et al. 2012).

Round Goby appear to be tolerant of high conductivity, which would also indicate a high tolerance to TDS and chloride concentrations. The majority of individuals were collected at sites with specific conductance between 800-1200 μS/cm, with more than 50 individuals collected at sites possessing specific conductance over 1600 μS/cm. In its native range, Round Goby inhabit the brackish waters in the Sea of Azov, the Sea of Marmara, and the Black Sea, making it unsurprising high specific conductance levels are tolerated.

Total Suspended Solids. Sediments from agriculture, construction sites, and industrial sources contribute to TSS pollution in the Des Plaines River watershed. Round Goby densities were significantly affected by TSS. Fewer individuals were collected at sites with high TSS concentrations. Physiological and behavioral effects have been recorded in fishes as TSS concentrations increase. Gill damage, foraging behavioral modifications, and reduced predator avoidance have been observed in other species (Bash et al. 2001). Round Goby avoidance of high volumes of TSS could be, in part, these factors, or decreased interstitial spaces between natural substrates due to TSS-caused siltation.

Dissolved Oxygen. D.O. concentrations rely on numerous environmental conditions, including primary production and organic sediments. Highly organic sediments, primarily observed in smaller tributaries, contain bacterial decomposers that consume oxygen to break down detritus. High chlorophyll concentrations from sestonic and benthic algae, as well as macrophytes, use oxygen at night to complete their respective metabolic processes. Each scenario can result in hypoxic conditions, with high diel swings and very high daytime concentrations, and are prevalent throughout the Des Plaines River watershed.

Round Goby were primarily collected at sites where D.O. concentrations ranged from 6 mg/L to 12 mg/L, however, individuals were collected at sites where extreme conditions. The species was observed at sites with D.O. concentrations up to 16.13 mg/L and as low as 3.50 mg/L, indicating tolerance to low D.O. and wide D.O. swings. Sites with observed concentrations above 12 mg/L are susceptible to wide D.O. swings, causing very low overnight concentrations that are detrimental to sensitive species. The preferred range for Round Goby appears to be between 6 mg/L and 12 mg/L, however, the species is tolerant of low D.O. concentrations.

Temperature. Fish require environmental temperatures to regulate the efficiency of biological processes. Temperatures too warm or cold can lead to reduced activity or mortality. Riparian removal, channelization, groundwater, and point sources all affect stream temperature. Streams lacking canopy cover are prevalent in the study areas, exposing surface water to sunlight, and causing higher water temperatures. This is exacerbated where sluggish flows dominate coinciding with the hottest months of the year. 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). Observations in the Des Plaines River watershed indicate high temperatures limit Round Goby densities. Twelve sites had temperatures above 28°C where no more than 19 individuals were collected during those sampling events. It is unlikely that temperatures in the Des Plaines drainage are above 30° beyond a few hours in the afternoons on the hottest days of the year. This may change through the added variable of climate change warming waters that are not protected by canopy cover, which is common in the region.

Habitat. High-quality and diverse habitats that include natural substrates free from silt and embeddedness, diverse cover types, and good quality pool-run-riffle sequences are essential for diverse fish assemblages. When most or all of these factors present at a site a higher QHEI score is recorded. Round Goby favor areas that include rock-type substrates (Boulder, cobble, and gravel), aquatic macrophytes, and slower flows (Ray and Corkum 2001; Reid 2019; Taborelli et al. 2008; Brownscombe and Fox 2012; Raab et. al. 2017). The high-quality substrates, diverse cover types including aquatic macrophytes, and slower flows are prevalent throughout the Des Plaines River watershed. Also prevalent are riparian removal, bank erosion, and channelization. Both positive and negative habitat attributes were present at each site to varying degrees. There was no differentiation in the QHEI scores for each stream size, which could explain the weak relationship shown in Figure 6. Fewer or no individuals were collected at headwater and large river sites, but habitat scores from those sites remain a part of the analysis. In addition, the degradation of riparian corridors, less desirable land uses, and other factors may limit the QHEI score at sites where Round Goby were numerous.

Future Research. 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 very real possibility. Further research needs to be conducted on whole fish assemblages inhabiting the same sites as Round Goby 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 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) will also need to be examined where pre- and post-introduction data exists. It is a tool for determining impairment causes that include habitat and pollution. 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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