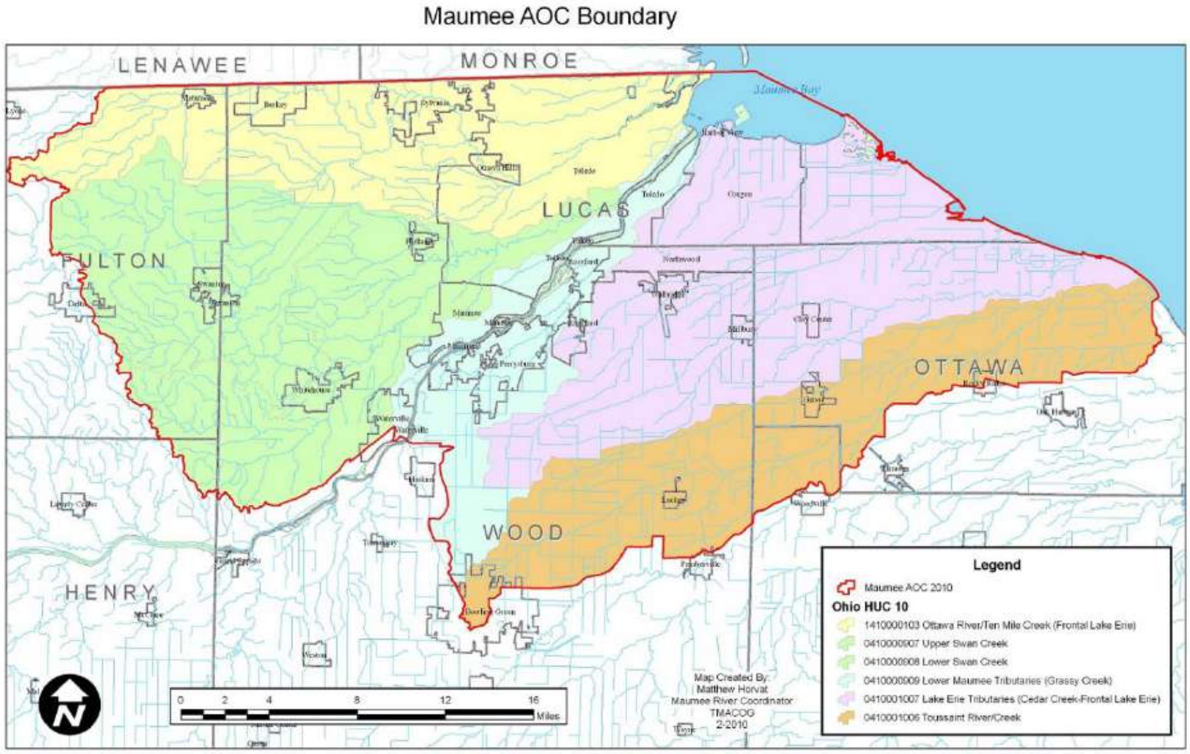
Identification of Optimal Sites for Maumee AOC Restoration Actions in the Lower Maumee River

Summary of Recommended Restoration Activities



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Project sites and specific recommendations

The following recommendations are meant to augment and protect habitat in the lower Maumee River from the Audubon Islands downstream to the Rt. 75 bridge for the benefit of fish and invertebrate species. These recommendations are based on a combination of fish and invertebrate catch data and habitat data collected in summer 2019, existing knowledge of the Maumee's fluvial processes and historical conditions, and literature review of other restoration activities and habitat types which can benefit these communities as outlined above. In general, the preservation and creation of large islands in the main channel in this reach of the Maumee will aid in the increase in biotic index scores. We suggest the installation of structures such as rip rap dikes (wing or chevron) to aid in the accretion of sediments around existing island complexes and for creation of new island complexes, promotion of SAV growth in island coves, native vegetation plantings, and installation of woody debris near sites severally lacking in potential structure/cover for fish. Below, we give specific recommendations for each site which are displayed across four maps, and the priority of each project has been ranked. Prioritization for each project is based on a combination of anticipated effort/cost (none, low, moderate, high), confidence of success in increasing biotic index scores (low, moderate, high), the need for a particular project based on the ecological state of the project site (low, moderate, high) and the likelihood of unintended impacts on fluvial processes that could have negative ecosystem effects (none, low, moderate, high). The projects are scored relative to the other projects – for example, if the need for a project is ranked as "low", it does not necessarily mean it is unimportant, it means it is simply less important than other projects being considered. Each qualitative metric score had a corresponding numerical score (e.g. for anticipated effort, numerical scores were as follows: none = 1, low = 2, moderate = 3, high = 4). The sum of these numerical scores determined priority ranking. In cases in which the sum was equivalent across two or more project sites, the scores for need and success confidence took precedence.

Table 1. Segment 1 (Audubon Islands to Turnpike bridge) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
1	- juvenile walleye captured in trawls - known walleye spawning ground - July and August electrofishing IBI score was one of the highest	*Protection* - Avoid changes to flow or structures around island	- walleye spawning area preservation	none	high	none	high	**1**
2	- shoreline classification indicated lack of habitat complexity - shoreline lacked vegetation to support shoreline structural integrity - low total fish abundance across August sampling methods - low total fish abundance and	- Install root wads, submerged trees/logs, or other woody debris along bare shorelines - Plant native vegetation along bare shorelines	- Fish/invertebrate habitat augmentation - bank stabilization	low	high	low	moderate	**9**

	richness for July electrofishing - low Unionid mussel abundance and richness							
3	- shallow cove environment and protection from harsh flows could help generate SAV - low total fish abundance and richness for July electrofishing near mouth of cove - low July and low August IBI near mouth of cove - low percent EPT abundance and invertebrate taxa richness on Hester-	- Install rip rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	low	moderate	**12**

	Dendies near mouth of cove							
4	- shoreline classification indicated lack of habitat complexity - shoreline lacked vegetation to support shoreline structural integrity - low total fish abundance across August sampling methods - low total fish abundance and richness for July electrofishing - low July and moderately low August IBI	- Install root wads, submerged trees/logs, or other woody debris along bare shorelines - Plant native vegetation along bare shorelines	- Fish/invertebrate habitat augmentation - bank stabilization	low	high	low	moderate	**8**

5	- shoreline classification indicated lack of habitat complexity - shoreline lacked vegetation to support shoreline structural integrity - low total fish abundance across August sampling methods - low total fish abundance and richness for July electrofishing	- Install root wads, submerged trees/logs, or other woody debris along bare shorelines - Plant native vegetation along bare shorelines	- Fish/invertebrate habitat augmentation - bank stabilization	low	high	low	moderate	**7**
6	- high Unionid mussel species richness	*Protection* - Avoid changes to flow or structures around island	- mussel bed preservation	none	high	none	high	**5**
7	- fish species richness high for August electrofishing despite exposed shoreline - low total fish abundance across	Install rip-rap wing-dikes along exposed shoreline	- Fish/invertebrate habitat augmentation	moderate	moderate	moderate	low	**13**

	August sampling methods - low total fish abundance and richness for July electrofishing - low Unionid mussel richness							

Figure 1. Segment 1 of study reach with project sites labeled.

Table 2. Segment 2 (Turnpike bridge to exposed shoreline downstream of Marengo Island) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
8	- high August total fish abundance (gizzard shad dominated), but low richness across August sampling methods - low total fish abundance and richness for July electrofishing - low July and August IBI - shoreline classification indicated lack of habitat complexity	Install root wads, submerged trees/logs, or other woody debris along bare shorelines	- Fish/invertebrate habitat augmentation	low	high	low	moderate	**10**
9	- low total fish abundance and richness across August sampling methods	Install chevron-style rip-rap dike at upstream end of island	- sediment accretion/island growth	high	low	high	high	**16**

	- low total fish abundance and richness for July electrofishing - low July and August IBI - low Unionid mussel abundance and richness - small island, lacks protection from flows							
10	- not sampled, but has no protection from flows which may impact fish and invertebrate communities	Install rip-rap wing-dikes along exposed shoreline	- Fish/invertebrate habitat augmentation	moderate	low	high	moderate	**19**

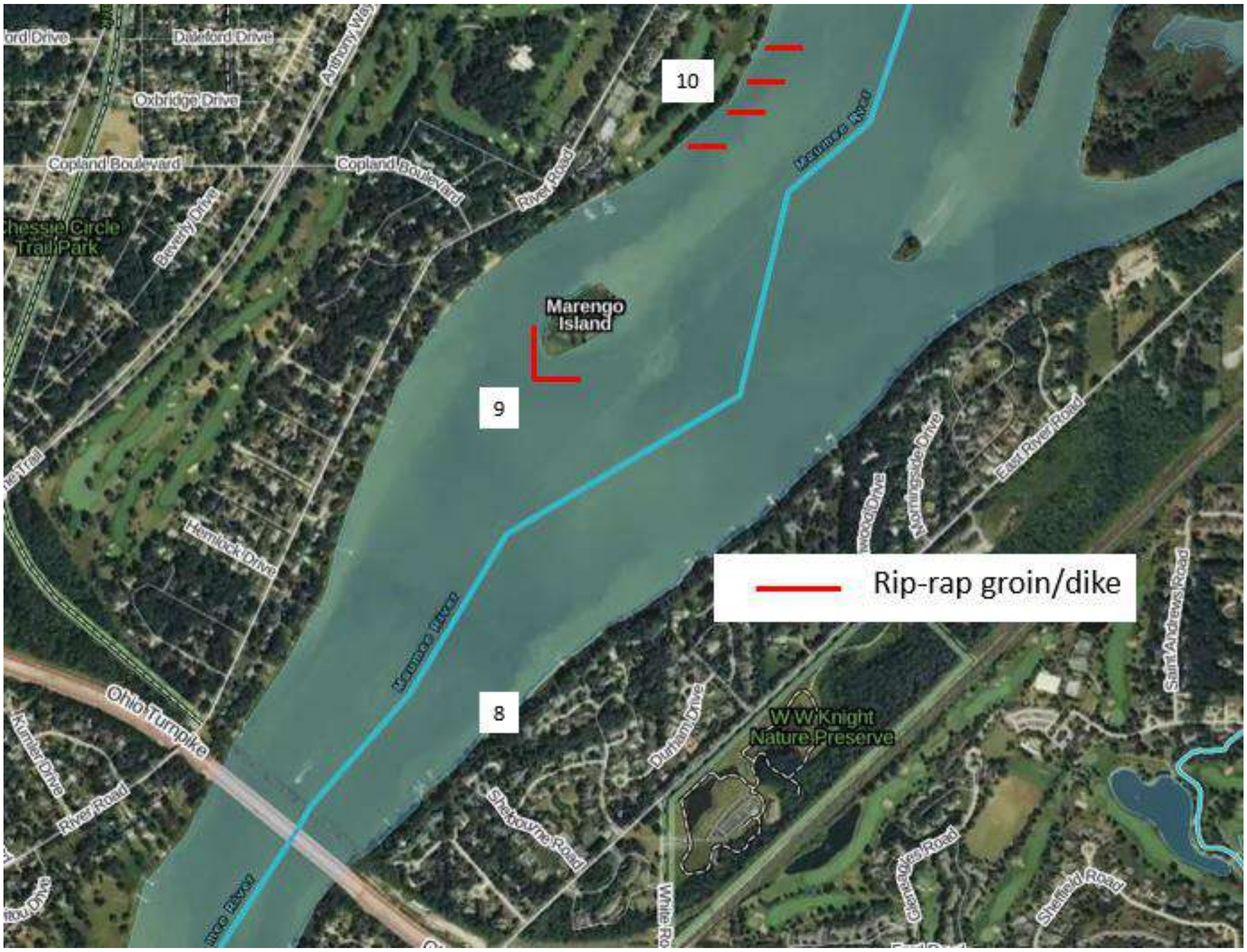


Figure 2. Segment 2 of study reach with project sites labeled

Table 3. Segment 3 (Grassy Island to Delaware/Horseshoe Island Complex) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
11	- high Unionid mussels abundance (individuals >10mm) and richness	*Protection* - Avoid changes to flow or structures near upstream end of island	- mussel bed preservation	none	high	none	high	**3**
12	- low total fish abundance and richness across August sampling methods - low total fish abundance for July electrofishing - low July and August IBI - low percent EPT abundance and moderately low invertebrate taxa richness on Hester-Dendies	Install rip-rap wing-dikes along exposed shoreline	- Fish/invertebrate habitat augmentation	moderate	moderate	high	moderate	**14**

13	- historical island completely removed – could potentially re-establish	Install chevron-style rip-rap dike upstream of historical island site	- sediment accretion/island growth	high	low	high	low	**20**
14	- shallow cove environment and protection from harsh flows could help generate SAV - low August and moderately low July IBI - low percent EPT abundance and invertebrate taxa richness on Hester-Dendies	- Install rip-rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	moderate	low	**17**
15	- shallow cove environment and protection from harsh flows could help generate SAV - low total fish abundance and richness across August sampling methods in the side	- Install rip rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	low	moderate	**11**

	channel this cove faces (Grassy Island side channel)							
16	- highest Unionid mussel abundance and richness across sites	*Protection* - Avoid changes to flow or structures near upstream end of island	- mussel bed preservation	none	high	none	high	**2**
17	- shallow cove environment and protection from harsh flows could help generate SAV - low percent EPT abundance on Hester-Dendies	- Install rip rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	moderate	moderate	**15**

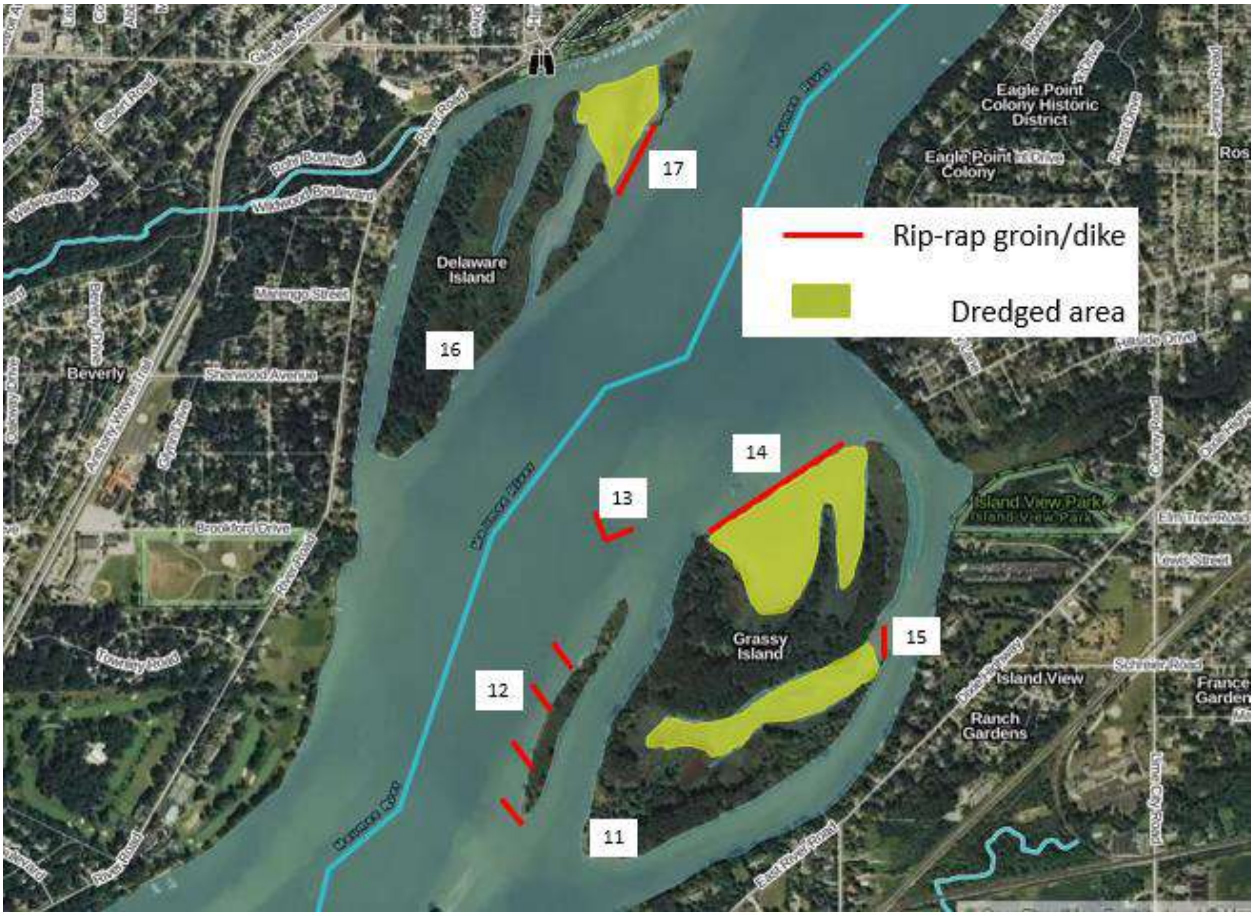


Figure 3. Segment 3 of study reach with project sites labeled

Table 4. Segment 4: (Clark Island to Rt. 75 bridge) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
18	- high Unionid mussel abundance (individuals >10mm)	*Protection* - Avoid changes to flow or structures around island	- mussel bed preservation	none	high	none	high	**4**
19	- island complex was historically larger - low total fish abundance and moderately low richness across August sampling methods - low total fish abundance for July electrofishing - low total invertebrate abundance and percent EPT taxa on Hester Dendies	Install chevron-style rip-rap dike at upstream end of island	- sediment accretion/island growth	high	low	moderate	moderate	**18**

	- moderately low Unionid mussel abundance and richness							
20	- not sampled, existing rip-rap can benefit fish and invertebrate communities	*Protection* - Keep rip rap structures previously installed to fix Rt. 75 bridge	- Fish/invertebrate habitat augmentation	none	moderate	none	high	**6**

Figure 4. Segment 4 of study reach with project sites labeled

Recommended project prioritization summary

Highest Priority (Rankings 1-6; Project sites 1, 16, 11, 18, 6, 20)

The highest priority sites are those in which we are trying to protect already high-quality habitat. These sites require no action other than simply not disturbing them. These projects include sites that contain known spawning grounds for walleye (project site 1), potential important fish and invertebrate habitat (site 20), and areas of high Unionid mussel abundance and/or richness (sites 16, 11, 18, 6). Site 1 is ranked the highest of all these sites as it was deemed important from both previous knowledge and our catch data. In regards to the Unionid mussel protection sites, 16 had the greatest Unionid richness and abundance of all mussel sites across both mussel size classes, and thus is ranked highest among them, while with the other sites the richness and/or abundance of a particular size class was lower. Site 20 ended up being ranked the lowest out of these sites since we did not actually sample there, thus we can only say with some confidence that this is an already high quality fish/invertebrate site.

Moderate-High Priority (Rankings 7-10; Project sites 5, 4, 2, 8)

In general, the moderate-high priority sites are those which call for the installation of habitat augmenting features such as root wads or downed trees along the shoreline. These projects are low cost, and can be a quick and effective means of attracting fish and invertebrates to these sites and supporting these populations in the future. All of these sites demonstrated some lack of habitat heterogeneity, which was reflected in fish and/or mussel catch. Project site 5, which signifies the center of the western shoreline of Grape Island, lacked any semblance of significant riparian vegetation or woody debris besides some tall grasses, and also thanks to low August fish abundance and low July fish abundance and richness, was ranked the highest out of these sites. Site 4 also had low August fish abundance and low July fish abundance and richness and contained a bare shoreline, but did contain some downed woody debris, and thus is ranked just below project 5. Site 2 also had these same issues, with the addition of low Unionid mussel richness and abundance, but did already have some pre-existing riparian vegetation and downed tree branches overhanging the shoreline, and is thus ranked just below site 4. Site 8 did contain rip-rap habitat which is an improvement over the mostly bare shorelines of project sites 5, 4, and 2, and thus is ranked lower. Despite this rip-rap however, the site still had issues with fish species richness during August sampling and both richness and abundance during July, which may be a result of the exposed nature of this shoreline to high flows. The addition of woody debris at this site could create some disturbance to these high flows and will add additional habitat heterogeneity to attract more species of fish.

Moderate-Low Priority (Rankings 11-16; Project sites 15, 3, 7, 12, 17)

The moderate-low priority sites are those which call for habitat augmentation through the use of dredging activities and flow barriers outside of coves to generate SAV beds and/or river training structures such as wing dikes that will require moderate to high costs, may have a moderate to high degree of unintended impacts on flow, and may have a few issues regarding success confidence. For example, the projects related to SAV production may face considerable challenges. This is mostly due to the high turbidity of the Maumee River which has contributed to the prevention of SAV growth in the first place, along with invasive plant growth such as Phragmites. Dredging these coves to 1.5 m may help with both these problems because it is at the threshold depth of where Phragmites and other emergent plants in general begin to be discouraged from growing and it may be shallow enough to negate the effect of the turbid water on blocking sunlight and thus inhibiting submerged plant growth. However, it is unknown whether the turbid waters will still impact SAV growth at that depth, so success confidence for these projects is only ranked as moderate.

Site 15 is ranked the highest of the moderate-low priority projects as it calls for the dredging of a cove whose mouth faces downstream into the Grassy side channel, so overall effects of flow are likely to be minimal. Also, although the cove itself was not sampled, August fish richness, abundance and IBI scores in the side channel it faces were low, so work in this cove could improve the fish populations in this area. Site 3 calls for a similar project, and is also unlikely to majorly affect flows or downstream communities as the mouth of the cove faces downstream. Combined August fish catch data indicates richness and abundance were slightly better near this site than near site 15, thus it is ranked lower on the priority list. Site 7, which calls for installation of wing dikes, may have more of an impact on flow, but the negative consequences of this is ranked only as moderate as no high-quality sites were identified immediately downstream of this site. Site 12, on the other hand, which also calls for wing dikes, presents the same flow issues, but potentially with greater consequences as a the site which contained our best Unionid catch (site 16) is just downstream of site 12, and thus is ranked lower. Site 17 calls for another SAV augmentation project, and although this cove was not sampled for fish directly, sampling around the unnamed island directly downstream of it demonstrated moderate fish abundance and richness according to combined August catch data, thus its priority was ranked below 12.

Lowest Priority (Rankings 17-20; Project sites 9, 14, 19, 10, 13)

Like the moderate-low priority projects, these also include a combination of SAV habitat augmentation and river training structure installation projects, but with potentially higher costs and/or lower reward. For example, several of these projects call for the installation of chevron dikes to either influence growth of existing small islands or to aid in the growth of new ones, but these projects may be some of the most costly. To be successful, these projects may require the movement of previously dredged material downstream of the dike to aid in success of island creation. Additionally, these projects would generally take place mid-channel in deeper waters than the wing-dike projects, and this would require more material to construct the dikes. Although the chevron dike projects could have the potential to be some of the most important given the benefits these island complexes can bring to the region and the area’s history of island loss, it will take time for the new island land to fully develop and generate preferred habitat for fish and invertebrates. Consequently, it may be several years before measureable ecological improvements are seen from the chevron dike projects.

Of these lowest priority projects, project site 9 scored the best. Although the cost of the project is likely to be high, and the chevron dike flow diversion may potentially affect high quality habitat downstream (e.g. site 11), the ecological need for the project is high since this site demonstrated both low richness and abundance for fish and mussels across sampling dates and methods. Project site 14, which calls for SAV bed augmentation, although may cost slightly less and have lower flow impact than project 9, the fish richness and abundance across sampling methods in this cove did not indicate it was one of the more degraded sites, thus the need for the project is low. Project site 19 calls for another chevron dike to be installed and faces the same challenges as the chevron dike at site 9, but fish and mussel catch indicated this small island (Corbutt) was not as degraded as the small island near project site 9 (Marengo Island). Site 10 is another project recommended at a site that was not actually sampled, nor is it directly adjacent to a site that was sampled, so our confidence of success in this project is low. The wing dike flow diversion at this site could also potentially impact the upstream end of Delaware Island which had demonstrated high fish abundance and richness across sampling dates and methods. Project site 13 is ranked the lowest of all these projects. It received the lowest possible score in this ranking system, as the chevron dike project will likely have a high cost, high chances of impacting nearby fish and invertebrate communities by impacting flows, low need as the other islands provide other ample opportunities for habitat restoration, and low confidence in success as the development of this island and thus the ecological improvements could take several years to be detected.

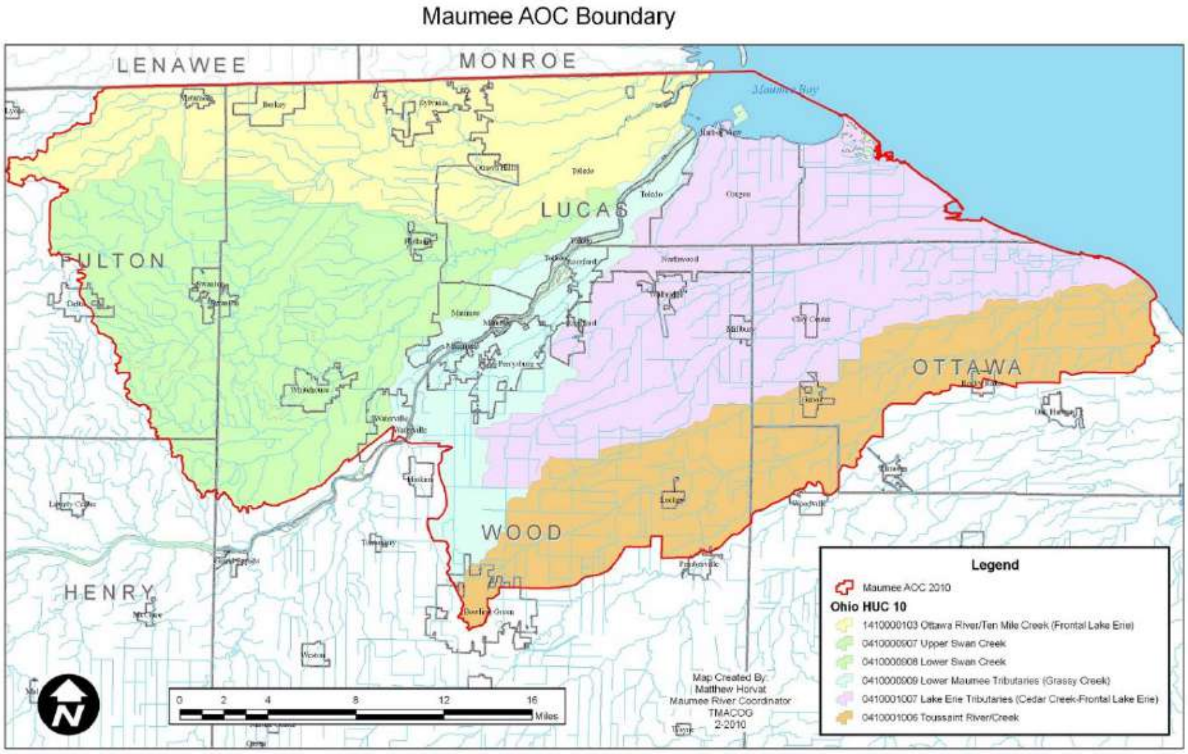
Benefits and next steps

If successfully implemented, these restoration projects could greatly benefit the fish and invertebrate communities in the Maumee River. Evaluating the financial and legal components of these projects will be an important next step in implementing these projects. Specifically, coordinating with engineers will allow us to estimate the project costs as well as potential impacts on fluvial processes in the river, and communicating with the various stakeholders who either own the land at each project site or make other use of it is vital to then making a final determination as to where projects can be carried out. Once this phase is complete and one or more projects are implemented, extensive monitoring must occur in order to ensure the fish and invertebrate communities are responding positively to restoration efforts. This project has established the spatial distribution of high-quality and degraded fish and invertebrate habitat in a biologically important stretch of the Maumee River, and has established a baseline of conditions by which further sampling and community evaluation should be compared to.

Although we cannot make exact predictions as to how Ohio EPA biotic community and habitat metrics (IBI, ICI, MIwb, QHEI) will be affected by these restoration projects, we are confident that many of these restoration projects will help these sites approach or meet Ohio EPA restoration targets for Warmwater Habitat (WWH) in order to remove BUIs affecting the region. In addition to removing three BUIs (3.) Degradation of fish and wildlife populations 6.) Degradation of benthos and 14.) Loss of fish and wildlife habitat), these projects could bring a variety of ecological improvements that are unique to this river. For example, in 2018, the Toledo Zoo began raising and stocking juvenile Lake Sturgeon (*Acipenser fulvescens*) into the Maumee River at Walbridge Park just downstream of the Delaware/Horseshoe island complex. Given the potential habitat improvements created by these projects, the suggested restoration activities may improve Sturgeon retention in the years to come. Additionally, given that 17 fish species which once historically spawned in great numbers in the Maumee River no longer do (Karr et al. 1985), we would expect to see a resurgence in the spawning activities of these fishes, particularly those which have yet to be extirpated from the region. For example, Northern pike, which are still present in the river but whose spawning activities were reduced in the river due to a loss of aquatic vegetation, may benefit directly from restoration projects which directly address the lack of submerged aquatic vegetation in the river. Overall, this Maumee fish and invertebrate assessment, the restoration efforts which will emerge from it, and the subsequent monitoring and evaluation of their benefits will play a fundamental role in eliminating the AOC status of the Maumee.

FINAL REPORT

Identification of Optimal Sites for Maumee AOC Restoration Actions in the Lower Maumee River



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Introduction

The lower Maumee River runs through the heart of the Maumee Area of Concern (AOC), which comprises nearly 800 square miles at the western end of Lake Erie, part of the “Great Black Swamp” pre-settlement. The installation of agricultural drainage in the Great Black Swamp along with urbanization, shoreline hardening, and dredging for shipping have altered the physical habitat template and ecology of the Maumee River and nearby tributaries to Lake Erie. Sediment-laden waters have also triggered the loss of hot spots for primary and secondary production in slack waters (e.g., macrophyte beds) that would support diversity among macroinvertebrates and fish populations and thereby contribute to high scores on indices of biotic integrity. Habitat degradation in the lower Maumee region is overwhelmingly affected by factors such as sediment loading that originate outside the boundary of the Maumee AOC and cannot feasibly be significantly altered due to economic and political realities; regeneration of the formerly expansive wetland network on the now-terrestrial landscape is prohibitive. Thus, to provide realistic and feasible recommendations for removing impairments to aquatic habitat and fish and invertebrate communities, and ultimately removing the “AOC” designation of the region, it is essential to identify main-channel fluvial habitats that support or could be enhanced to support river biota.

In May 2018, the Maumee AOC Advisory Committee (MAAC), Subcommittee on Aquatic Habitat and Species, hosted a workshop with approximately 50 research scientists, engineers, and environmental managers to identify pragmatic solutions that could positively affect the Maumee AOC and make progress toward removal of Beneficial Use Impairments (BUIs) and ultimately remove the Maumee AOC from the list of Great Lakes AOCs, a binational federal program administered by the US Environmental Protection Agency (EPA).

After an overall synthesis of available data and environmental conditions, a consensus emerged among workshop participants that large-scale remediation efforts within the lower Maumee River would require alterations within the river proper rather than on a watershed scale. Expert analysis of Ohio EPA fish and macroinvertebrate assessments within the AOC boundary revealed that restoration of wetland-type habitat would be most beneficial (Schaeffer et al. 2018). The teams focused their attention on the few remaining locations with high potential for restoration. Workshop participants noted few, if any, areas available for restoration in the river reach between I-75 and the river mouth that would be cost-effective. There did, however, appear to be in-river opportunities from Perrysburg (~RM15) downstream to I-75 (~RM7) where remnants of islands still provide some aquatic habitat. Finally, participants made clear their desire to avoid degrading any existing high-quality habitat in the river.

Post-workshop synthesis by the Subcommittee members revealed the need for additional, finer-scale information on the current conditions of target potential project sites, their potential for restoration, and the clear designation of existing high-quality habitat. The Subcommittee identified this information as critical for prioritizing and developing potential project sites, establishing reasonable and achievable restoration targets, and preventing the degradation of existing high-quality habitat. The first year of this study is targeted directly at the informational needs with regard to the lower Maumee River; subsequent informational needs as identified by the Subcommittee or MAAC may be addressed in future years.

Existing Conditions, History and Restoration Projects Review

Current conditions and importance of Maumee River

The Maumee River and its watershed is utilized for a variety of agricultural, industrial and recreational purposes in Northwest Ohio. An extensive ditch system removes 70% of the watershed for use in 3.2 million acres of surrounding farmland (American Rivers, Inc. 2019) and it is used as a major transportation corridor for commercial freight entering and leaving the Port of Toledo, which is one of the largest ports on the Great Lakes (Ohio DNR Office of Coastal Management). Four Ohio municipalities draw drinking water from the Maumee (Ohio EPA 2014), as well as Campbell's Soup Supply Company for 1,200 of their employees. The region maintains a variety of recreational uses and benefits, and the segment of the lower Maumee from Defiance to Rt. 20 bridge in Perrysburg was even designated as a State Recreational River by the Ohio Department of Natural Resources in 1974. Furthermore, the 22.8 mile stretch of the lower Maumee River encompassed by the Maumee AOC alone is home to nearly a dozen metroparks and recreational areas, three boat launches, and 14 official access points for fishing, kayaking and canoeing along its course (Metroparks Toledo). The rivers utility for fisherman is a well-known commodity in the Midwest – the annual Walleye Run which occurs during March/April of every year in the Maumee River, is home to the largest migration of walleye east of the Mississippi River (Kaptur 1999). Thousands of fisherman from the region and across the country crowd the banks of the Maumee during these months to try their hand at capturing some of the hundreds of thousands of walleye which make their way up the river every year (Carpenter 2001).

Despite historical degradation, the Maumee River maintains biological value for a variety of organisms. For example, among the three riverine stocks of larval walleye that migrate into Lake Erie (Maumee, Detroit and Sandusky Rivers), the Maumee River contributes the greatest number of larval walleye (DuFour et al. 2015). The river is known to support runs of a variety of other migratory fish from Lake Erie as well (Trautman 1981). Better Management Practices (BMPs) in the watershed have even improved water quality and improved larval fish diversity in recent decades (Mapes et al. 2014). Recent Ohio EPA data suggests that fish communities have been improving in the Maumee River over the past 28 years, with fifteen pollution sensitive taxa being collected in 2012 – 2013, which is seven species more than a previous survey in 1997 (Ohio EPA 2014). Beyond fish species, the lower Maumee River has been designated as an IBA (Important Bird Area) by the Audubon Society. The river provides a migratory corridor for a variety migrant land birds and gull species (Audubon Society).

Historical changes in the Maumee River

The lower Maumee River has undergone a variety of geologic, hydrologic, and biological changes since agricultural and industrial development began in the region in the 1800s. In regards to the biology of the river, a variety of species that once spawned in the Maumee River no longer do. Specifically, 17 species that historically spawned in the Maumee have been extirpated over the past century (e.g., Muskellunge *Esox masquinongy*, Northern pike *Esox luscious*, and Lake sturgeon *Acipenser fulvescens*) (Karr et al. 1985). For example, Northern pike used to spawn in formerly abundant vegetated wetland habitat, but much of this habitat was eliminated by draining for agriculture and channelization (Mapes et al. 2014). Large beds of aquatic vegetation were present in the Maumee River until about 1950, but this is now a rarity

(Trautman 1981). Burrowing mayflies (Hexagenia spp.) were the dominant macroinvertebrate in Maumee Bay and much of Western Lake Erie until the 1960s where they were nearly extirpated from the region by extreme eutrophication (Trautman 1981). They do appear to be making a comeback, but have yet to completely reestablish (Krieger et al. 1996).

Alluvial islands are critical habitats in riverine ecosystems (e.g. Figure 1). Geologically, the lower 7 miles of the river undergoes modifications every year through annual dredging activities which removes 850,000 yds^3 of sediment annually, but this is unfortunately a necessity to maintain travel to and from the Port of Toledo due to high sediment deposition from the surrounding agricultural areas. In the lower Maumee River reach of interest for this study in particular, gravel and clay dredging activities may have been the cause of a rapid decline in island size that was seen between 1970 and 1983 (unpublished data). The total area of these islands have been reduced by, potentially up to 42% since 1935 (unpublished data).

Figure 1. Audubon Islands Nature Preserve in the lower Maumee River is an example of in-channel habitat critical to the ecology and functioning of large river ecosystems.

In regards to hydrology, increased prevalence of impervious surfaces created through heavy urban development in the Maumee AOC has contributed to increased runoff and thus increased river flows and flood frequency. Some of the most drastic increases have occurred fairly recently - between 1997 and 2006, the percentage of urban land use increased nearly 13% in the lower Maumee watershed (Natural Resources Conservation Service 2009). The affects are being seen within the Maumee AOC - in the Lucas County portions of the Swan Creek watershed for example, flood flows have increased 17 to 85 percent from pre-settlement times (Maumee Remedial Action Plan Committee 2006). Given that the watershed immediately surrounding the main-stem of the lower Maumee River (HUC 041100009 09 Lower Maumee Tributaries) is 34% developed land (Tetra Tech Inc. 2012), similar runoff affects have surely modified the flow regime of the main-stem lower Maumee River.

Potential high-quality habitats

Remnants of islands that were historically reduced in size still remain between river mile 15 and river mile 7. Given the important role that alluvial island complexes have in supporting fish and invertebrate communities (Thorp 1992; Gurnell and Petts 2002), this remaining cluster of islands is thought to contain high quality habitat and provide the greatest opportunity for restoration of habitat in this stretch of the Maumee.

Some of these sites (from upstream to the downstream end of the study reach) include:

- Audubon Island (including internal channels and coves)
- Wetland downstream of Orleans Park on Perrysburg side
- Downstream of the Maple Street boat launch (a side channel)
- Lowland peninsula downstream of Fort Miami Park
- Delaware Island (including Delaware Creek mouth)
- Grassy Island (including Grassy Creek mouth)

What approaches have been successful in other river ecosystems?

In other degraded river systems across the US facing similar challenges to the Maumee, a variety of restoration approaches have been successful in improving water quality, habitat for fish, macroinvertebrates and other wildlife, and generally improving the ecological integrity of systems. These projects have been carried out over a variety of time frames and over several different spatial scales. In general, river restoration projects are thought to be more successful if carried out in the context of an entire watershed (Wohl et al. 2005), but even projects which focus on a single reach of river, whether in isolation or as part of a larger project, have been able to display benefits of their own. Regardless of time or spatial scale, successful restoration projects implement some form of adaptive management (Williams 2011) in which restoration objectives are established, the approach is carried out, and the restoration benefits are monitored and learned from in order to improve the existing project or benefit subsequent ones (Theiling et al. 2015; Baril et al. 2019).

To date, one of the largest river restoration projects ever carried out in terms of spatial scale and time implemented is the Upper Mississippi River Restoration (UMRR) Environmental Management Program (Theiling et al. 2015). Implemented in 1986 and continuing today, this project was meant to monitor environmental status and trends and restore degraded habitat on 1,200 river miles and 3 million acres of floodplain in the Upper Mississippi River watershed (Garvey et al. 2010; Sparks 2010), and was one of the first projects of its kind in large navigable rivers (Theiling et al. 2015). Restoration was carried out in the form of Habitat Rehabilitation and Enhancement Projects (HREP). Each HREPs are carried out in specific reaches and/or pools of the river, and are defined by a set of environmental objectives specific to each HREP, but all aim to restore degraded habitat to a more natural and higher functioning condition (USACE 2000). These environmental objectives are developed from and based upon a combination of data about existing conditions, local knowledge, and best professional judgment (Theiling et al. 2015). The primary issue addressed by many of these HREPs was aquatic and wetland habitat loss to backwater and secondary channel sedimentation (UMRBC 1982). Following project implementation, which primarily consisted of backwater flow management, island construction/enhancement, and water level management (Theiling 1995), all projects were monitored for design integrity of constructed features. Biological response was also monitored, but unfortunately only for a subset of projects (Theiling et al. 2015). Of the projects that have had biological response monitoring, knowledge from mistakes made in earlier HREPs has helped island construction projects in particular to begin to demonstrate fish population recovery, as well as improvements in macroinvertebrate and submerged aquatic vegetation distributions (Theiling 2015).

Smaller scale projects have had success as well, even if not focused on an entire watershed. For example, the Kissimmee River Restoration project in central South Florida focused primarily on the main river channel, and the river's adjacent floodplain (Society for Ecological Restoration). Unlike in the Mississippi River, this project sought to restore main channel and floodplain ecosystems by achieving primarily one goal: restoring historical flow conditions. This was accomplished mainly via changing water flow management practices in the river, and backfilling canals which had channelized the river. The project implements an extensive monitoring program to evaluate changes in the ecosystem in response to these changes. Despite a fairly narrow and focused scope of project activities, and although formal evaluation and monitoring is still ongoing, early observations are already pointing to improved water quality, improved macroinvertebrate communities, and increased waterfowl density as a result of restoring historical flow conditions.

Several restoration projects conducted in other Areas of Concern have already demonstrated some success. For example, the St. Clair River Area of Concern, which shared seven BUIs with the Maumee Area of Concern, is now one of eight AOCs that has finished all on-the-ground work. Similar to the Maumee, many of the BUIs affecting the St. Clair River are related to fish, wildlife and degradation of their habitat, and the watershed is defined by heavy agricultural land use, as well as intensive development around certain stretches of the main river (Bohling 2012). As in other AOCs, to address these issues the St. Clair restoration plan was established and carried out via a three stage Remedial Action Plan. Stage 1 addressed and identified the environmental challenges faced by the St. Clair, stage 2 outlines the strategies needed to eliminate these challenges, and then stage 3 synthesizes results of monitoring and evaluation activities and works to delist the St. Clair AOC if monitoring has shown that BUIs have been addressed by restoration activities. Ten habitat restoration projects have been implemented that led to the elimination of the Loss of Fish and Wildlife Habitat BUI in 2017

One specific project that contributed to the elimination of this BUI was the construction of spawning reefs in the Middle Channel of the St. Clair River. This project consisted of two years of assessment to determine best sites for spawning habitat (Bennion and Manny 2014), construction of limestone reefs, and post-construction monitoring of the reef success in attracting spawners, which indicated they were in fact being used by fish, including Lake Sturgeon (Fischer et al. 2018). Other projects conducted which eliminated this BUI included a variety of shoreline remediation projects, where vertical seawalls at five sites in the river were replaced by sloped banks with in-stream structure (e.g. root wads and boulders) (Fischer et al. 2018). Evaluation of the fish community post-construction indicated that the restoration improved the fish community (Fischer et al. 2018).

Maumee River AOC – past and current efforts

Since being classified as an Area of Concern in 1985, the Maumee AOC has also begun a three stage process towards delisting similar to that of the St. Clair AOC. Environmental problems and sources of these problems in the Maumee AOC were identified in the 1992 Remedial Action Plan (RAP), and subsequently the stage 2 Remedial Action Plan (RAP) in 2006 which outlined approaches to addressing these environmental issues was created in 2006. Since that time, several restoration projects have been underway in the Maumee AOC. One of these projects was completed in 2010 - the Ottawa River Great Lakes Legacy Act Cleanup - which sought to remove upwards of 260,000 yd^3 of sediment from the Ottawa River. In conjunction with restoration actions, the Ohio EPA and other state and local groups (e.g. University of Toledo, Midwest Biodiversity Institute, Tetra Tech, and others) have continued to extensively sample and classify the biological and physical characteristics of the Maumee River to guide restoration activities. In a 2012-2013 survey, for example, Ohio EPA sampled 23 sites in the main-stem of the Maumee River alone, five of which were in the lower 15 mile lacustruary that is the focus of this report. In this lower 15 miles of the main stem of the Maumee River, three restoration projects are currently underway or have been proposed. The Penn 7 restoration project aims to restore 59 acres of land that was formally a disposal facility on the lower Maumee River by converting it into coastal wetland habitat, and is currently in its engineering and design phase. The Delaware and Horseshoe Islands restoration project aims to enhance wetland habitat on an in-stream island complex, and a variety of recommendations have been made to accomplish this by Tetra Tech, Inc. The Cullen Park Wetland Restoration project, led by the Mannik and Smith Group, Inc., seeks to utilize dredge material from Maumee Bay to build a wetland complex near the mouth of the river.

This project aimed to continue and supplement the work already accomplished or currently underway in the Maumee AOC, with particular emphasis on enhancing fish and macroinvertebrate habitat in the main-stem of the river to eliminate BUIs 3.) Degradation of fish and wildlife populations 6.) Degradation of benthos and 14.) Loss of fish and wildlife habitat. Specifically, this project sought to characterize habitat and the fish and benthic macroinvertebrate community near and around island complexes situated between approximately river mile 15 and 7 of the lower Maumee River. This would allow us to identify and differentiate between sites which are of high quality and degraded sites which require habitat restoration. In doing so, we could clarify spatial distribution of restoration potential at a finer scale than is currently available, identify efficient restoration approaches at target project sites and to subsequently determine restoration project feasibility.

Methods

Study area and sites

Sampling occurred around 21 sites along an approximately 9.7 km segment of the Maumee River ranging from the Audubon Islands at the upstream end, and Corbutt Island at the downstream end (Figure 2). Sites were selected in order to have reasonable diversity of habitat/flow conditions being sampled (e.g. upstream/downstream ends of islands, side channel habitat, main channel habitat).

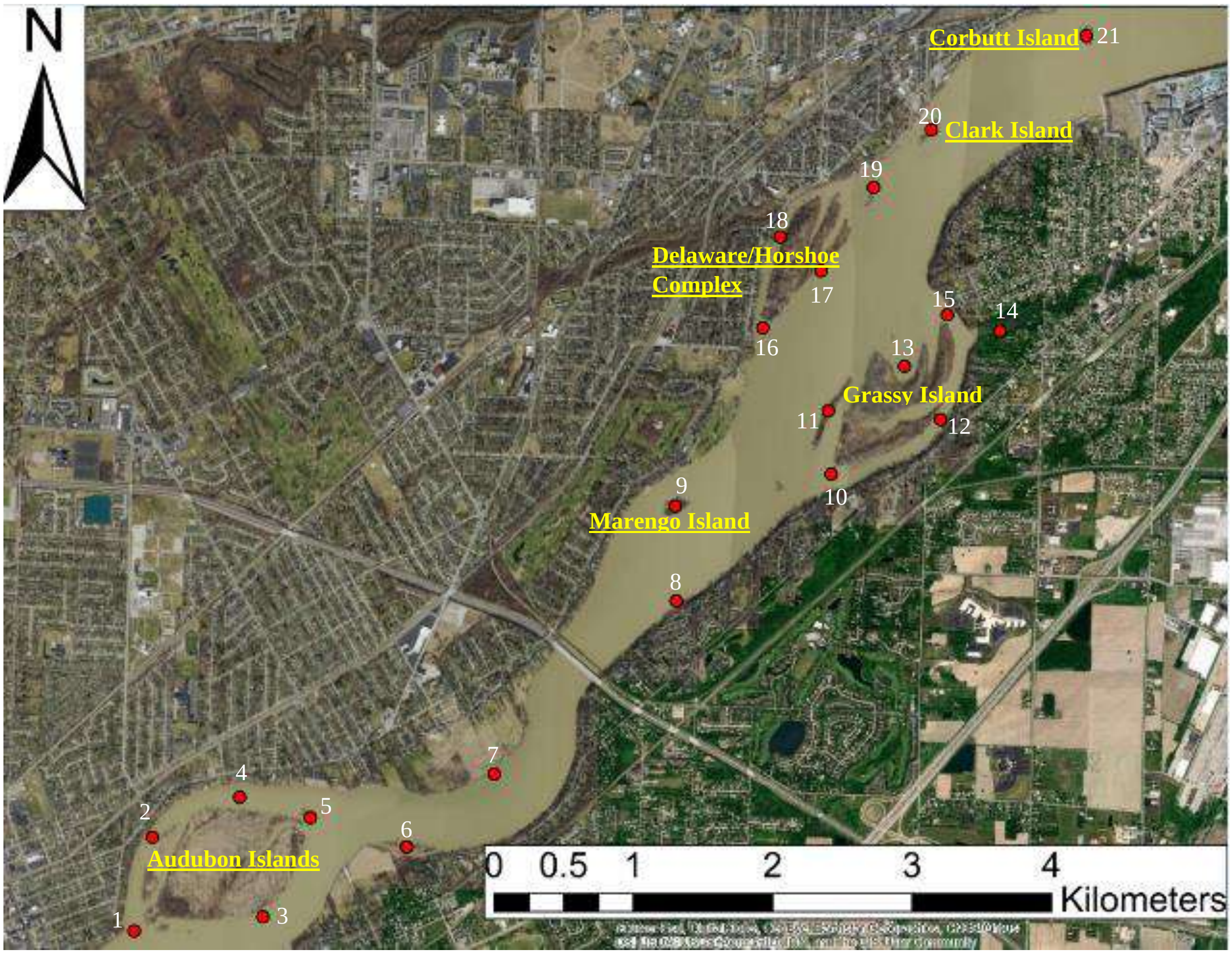


Figure 2. Fish and invertebrate sampling sites and island names.

Substrate classification

Substrate and depth data were collected during the last week of May and first week of June, 2019. Data were collected using Biosonics MX Aquatic Habitat Echosounder. Transects were parallel to one another and spaced approximately 100 m apart moving perpendicular to the shoreline when facing the main channel. Main channel transects were approximately 100 m in length and spanned 500 m stretch of shoreline for each site (six transects total for main channel sites). When in the side channels of islands, three transects were run parallel to the shoreline – one near each bank, and another down the middle of the channel. Substrate was categorized using Biosonics Visual Habitat software.

Ground-truthing was conducted using a 6 X 6 in Ponar grab sampler and hand tests of substrate. Sampling points were based upon 6 preliminary substrate classification groups generated in Visual Habitat. Each group present at each site was sampled once per site if present, leading to 76 ponar grabs being taken. Ground-truthing revealed inconsistencies between the Visual Habitat classifications and the ground-truthing. As a result, substrate was classified into four broad categories (from fine to coarse) from the ground truthing samples – clay/mud/silt, sand/silt, sand/pebble, cobble/bedrock – and the Biosonics results were not used for assigning substrate type to sampling transects. Fish trawl transects were assigned to one of these four substrate classes for all subsequent analysis based upon the closest ground-truthed points, previous substrate data collected via side-scan sonar in 2011 (Collier, USGS Mapping Tool), and expert opinion.

Abiotic data collection

A variety of abiotic variables (temperature (°C), dissolved oxygen (mg/L), turbidity (NTU), conductivity (µS/cm), pH) were measured around each island complex and fish sampling site once per month (June 18-19, July 12&16, August 9) using a YSI Pro Plus. In June and July, on the main channel side of islands or shorelines, two points were taken every 500 m – one nearshore and one 100 m offshore. In the side channels, three points were taken every 500 m – two on each shoreline, and one on the middle of the channel. All data collected was near surface (~0.5-1.0 m below surface). In August, to increase spatial resolution of abiotic data, spacing between points was reduced to 250 m. Once again, two points were taken every 250 m around sites facing the main channel (shoreline point and 100 m offshore) and three points were taken every 250 m in side channels (point on each shoreline and middle of channel), for a total of 185 sampled points. Both near surface (~0.5-1.0 m below surface) and near bottom (~0.5-1.0 m from bottom) data was collected in August. Interpolated maps of the August data (Appendix A) were generated for all abiotic attributes in ArcMap 10.6.1, and interpolated abiotic data was extracted for each August fish and mussel sampling transect for subsequent analysis.

Fish sampling

The fish community was sampled around each study site once in July 2019 via daytime electrofishing (5.0 GPP pulsator, Smith-Root or Infinity Control Box, Midwest Lake Electrofishing Systems, both operated at 60 pulses/s) and once per sampling method in August 2019 via daytime electrofishing (5.0 GPP pulsator, Smith-Root operated at 60 pulses/s) and bottom trawling (Missouri-style trawl).

Electrofishing consisted of two 3-minute transects at each sampling site with the boat operated at approximately 3-4 km/h as close to shore as possible (~0.5-1.5 m depth). In side channel sites, one transect was located on the shoreline of the island, while the other transect was on the opposite shoreline. In main channel sites, transects were conducted in succession along the shoreline of the island. For the smaller island complexes which did not have their own side channel (e.g. Clark and Corbutt), both transects were run in succession and typically wrapped around the entire island.

Bottom trawling for fish consisted of two to three 2-minute transects at each sampling site with the boat operated at approximately 1.9-2.4 km/h. In side channel sites, one transect was located nearest the island shoreline, and the other transect was located nearest the opposite shoreline. Trawls would run no closer than 10-15 m of shore to avoid being caught up in logs and woody debris. In main channel sites, one transect was located nearest the shore, and subsequent transects would run parallel to the first transect but in waters that were further from shore and approximately 1 m deeper. Transects around the smaller islands were run in the shadow of these islands (i.e. the downstream end – Clark and Corbutt islands), or along a depth gradient facing the main channel (Marengo Island).

All fish captured were identified to species, and if field ID was not possible, specimens were returned to the lab for verification. Larger fish (fish age 1 and up excluding Notropis minnows) were measured for total length (mm) in the field. Fish were also examined for DELT anomalies during August sampling events.

Shoreline habitat classification

Concurrent with electrofishing surveys, the shoreline habitat sampled was classified according to 5 general categories found amongst the sampling sites – Riparian vegetation, riparian vegetation with downed woody debris, hardened shoreline (e.g. rip-rap, armored shorelines), bare shoreline, and emergent vegetation (e.g. phragmites and lotus). The percentage of each of these shoreline types was estimated for each electrofishing transect, and used in subsequent analysis to determine effects of shoreline type on catch results.

Invertebrate sampling

The benthic invertebrate community was sampled via two means – Ponar grab samples and Hester-Dendy samplers. Ponar grab (6 X 6 in grab sampler) invertebrate samples were taken concurrently with substrate ground-truthing during the last week of June 2019. Sampling points were based open preliminary substrate classifications made in Visual Habitat software in which at least one sample per substrate group present at each site was taken. A total of 64 Ponar grab samples were collected for processing. Invertebrates were preserved in 70% ethanol and identified to the order or family level.

Thirty-one Hester-Dendy sampling units (3 Hester-Dendy samplers attached to a single cinderblock) were deployed according to substrate type as determined from the Ponar grab ground-truthing. With the exception of the number of samplers on each cinderblock (3 on our blocks vs 5 for EPA), each Hester-Dendy was constructed following EPA protocol (Ohio EPA 2015). Between 5 and 8 Hester-Dendy sampling units were deployed in a particular substrate type (clay/mud/silt, sand/silt, sand/pebble, cobble/bedrock) during the third week of July 2019, and were retrieved approximately 7 weeks later during the first week of September. Upon retrieval, Hester-Dendies were cut from the cinderblocks, placed in zip-lock bags filled partially with water, and brought immediately to the lab where invertebrates were washed from them and preserved in 70% ethanol. Invertebrates were identified to either the order or family level.

Unionid mussel sampling

Unionid mussels were collected via a modified Missouri-style trawl during the first and last weeks of August 2019. An additional set of chains were added to the trawl that was used for fish capture in order to weigh it down more and allow the trawl to better remove mussels from the substrate. Larger adult mussels would be scooped up by these chains and found within the net upon trawl retrieval, whereas juveniles were typically caught in the mesh by their byssal threads as the trawl dragged along the river bottom. Mussel trawl transects were 2 minutes long and the boat was operated at approximately 1.9-2.4 km/h. Rather than sampling around all 21 pre-determined fish sampling locations with a fixed number of transects, locations of mussel sampling transects were targeted for areas where mussels were thought to be present, and anywhere from 3 to 12 transects were run in a particular area. Since the borders of mussel beds tend to be quite distinct rather than showing a gradual tapering off of individuals (Todd Crail, personal communication), it was important to sample multiple transects in succession and at various depths to determine where the dramatic start and end points of these mussel beds were located. Upon capture, all unionid mussels were identified to species, measured for total length and returned near their capture location.

SAV sampling

Targeted sampling for potential beds of submerged aquatic vegetation (SAV) was conducted during the last week of August 2019. SAV was searched for using a Biosonics MX Aquatic Habitat Echosounder and rake tosses. Sampling sites were selected based on potential for the location to have submerged aquatic vegetation. These sites were: the side channel, the downstream end and the coves within the Delaware/Horseshoe complex; the cove at the downstream end of the Audubon Islands. One to three 100 m or more transects were run in each of these locations, and along each transect at 2-3 points, the rake was tossed and retrieved in three directions from the boat to collect SAV. No SAV was collected during these surveys, and thus SAV was not analyzed in Visual Habitat Software.

Statistical Analysis

All abiotic variables collected, including shoreline type (for electrofishing only), substrate classifications (for trawl only) and a flow metric (“side of island” which was used a proxy to represent different flow conditions) were all assessed for their effects on fish and mussel species richness, abundance, standardized metric (e.g. IBI) scores, and presence/absence of certain species and/or families of fish (e.g. walleye presence, centrarchids presence) for each sampled track from the August sampling events. Initially, each explanatory variable was regressed against these three responses, and regression trees were created in order to determine the variable most explaining variation in the data. Alternatively, the variables explaining the most variation in the species richness, abundance and IBI data was also explored via multiple regression analysis and AICc model selection. Multiple logistic regression analysis and subsequent AICc model selection was used to determine the influence of these factors on bivariate responses (e.g. presence/absence of walleye)

Results

Fish

Trawling

Fish diversity and abundance were highest around the large island complexes (Figures 3 & 4). Higher species richness would typically occur at either the upstream or downstream end of islands rather than side channels or main channel shorelines (Figure 5) as well as along tracks that were in shallower water (Figure 6). Other abiotic variables and substrate type did not strongly influence species richness and abundance from fish trawls (Appendix B).

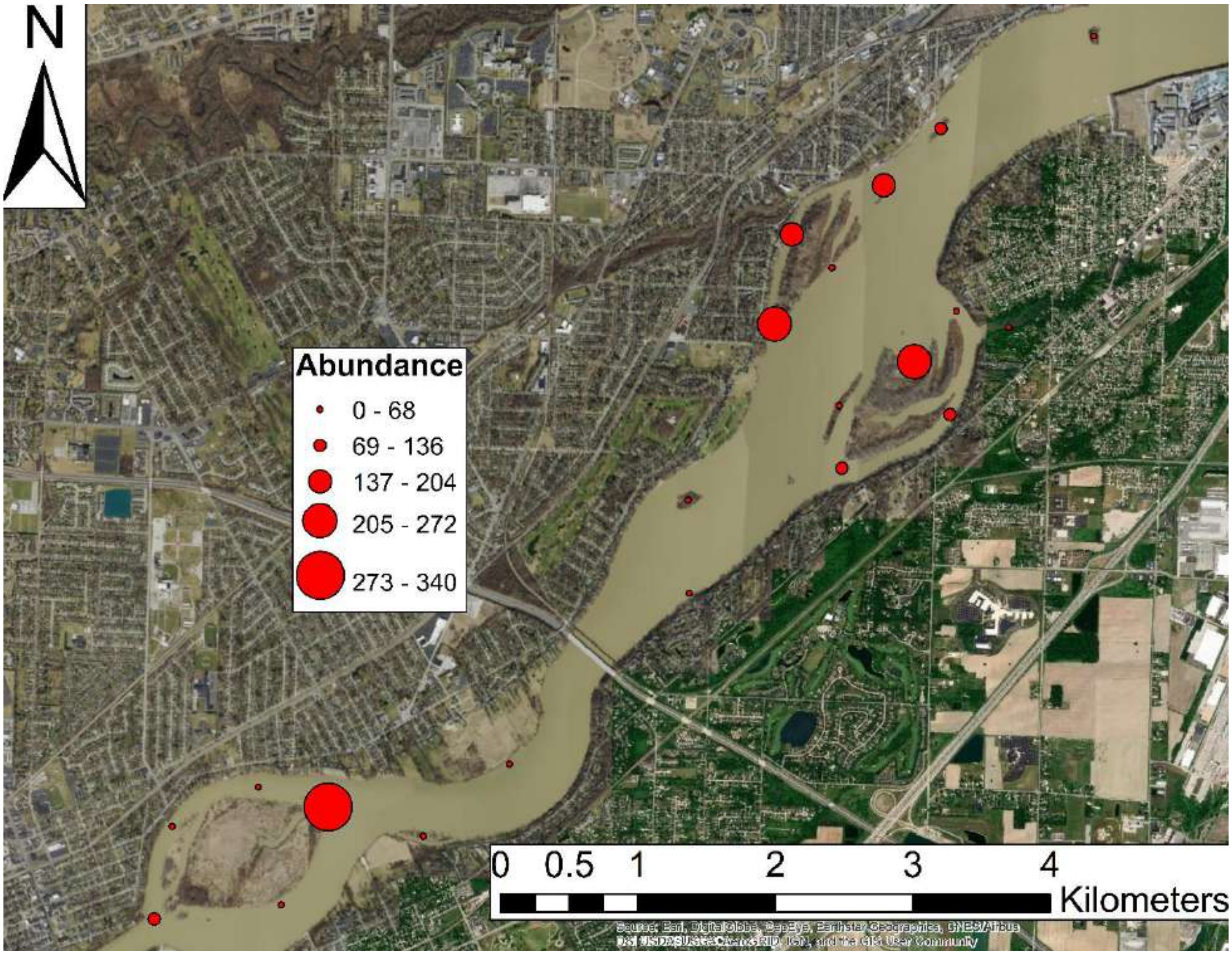
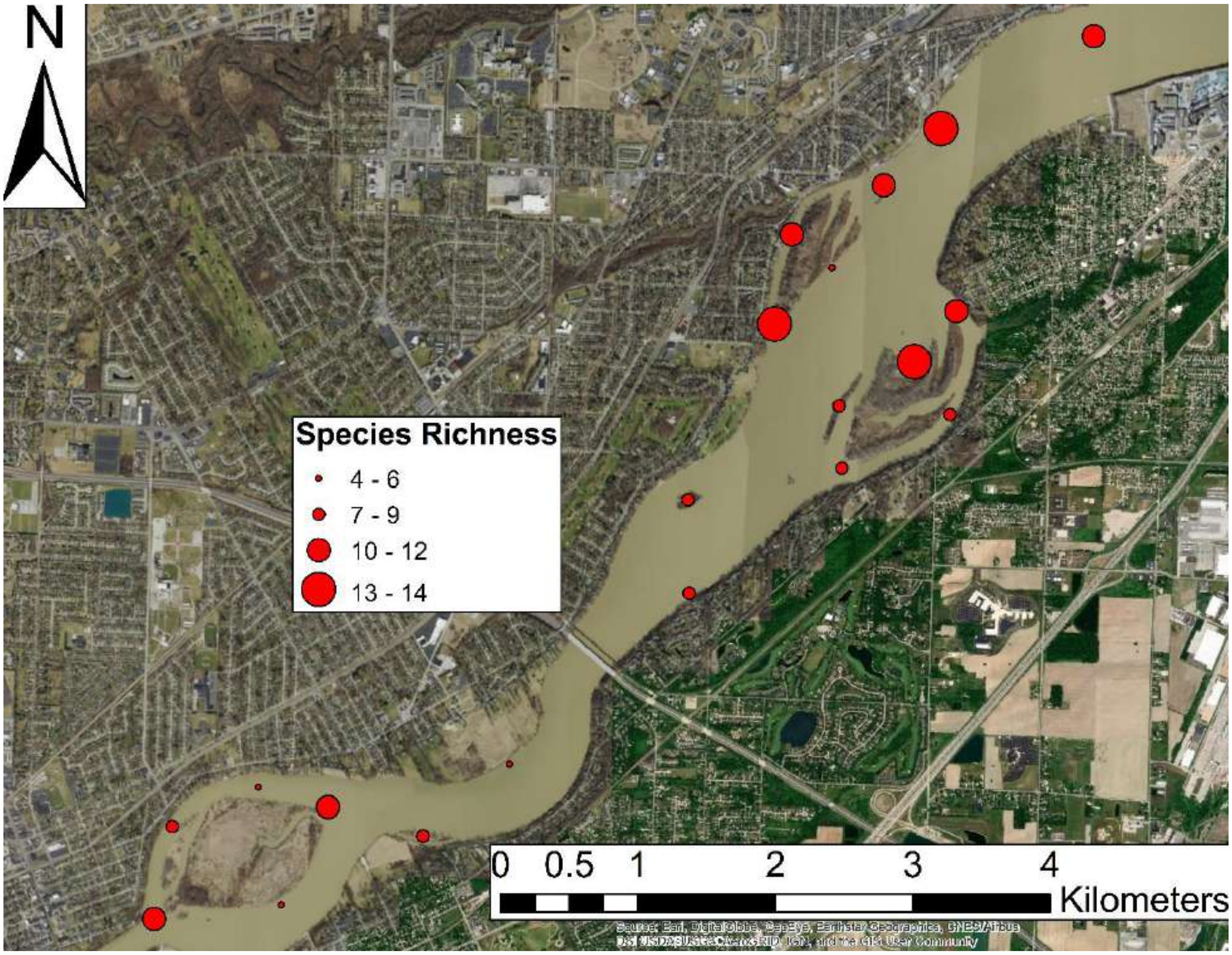


Figure 3. Fish trawl abundance at each site. Abundances are totals across two transects at each site. Young-of-year channel catfish are not included as they were often caught by the hundreds and masked other spatial relationships.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4. Fish trawl species richness at each site. Richness scores are overall scores across two transects.

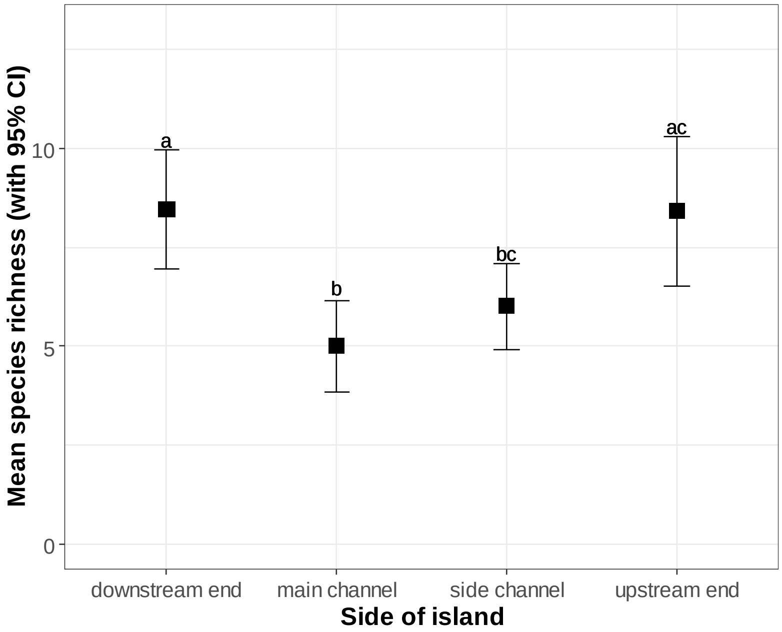


Figure 5. Mean species richness for fish trawl tracks located at different sides of islands and facing different channels. Side of island was assumed to be a proxy for flow conditions.

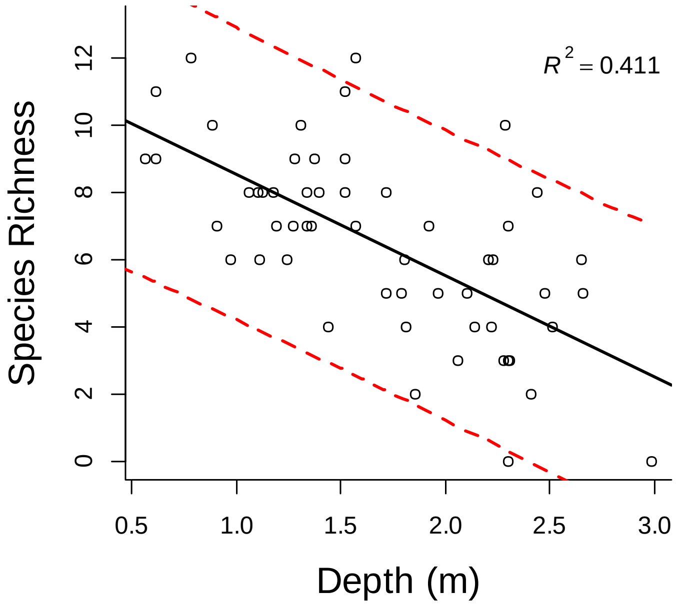
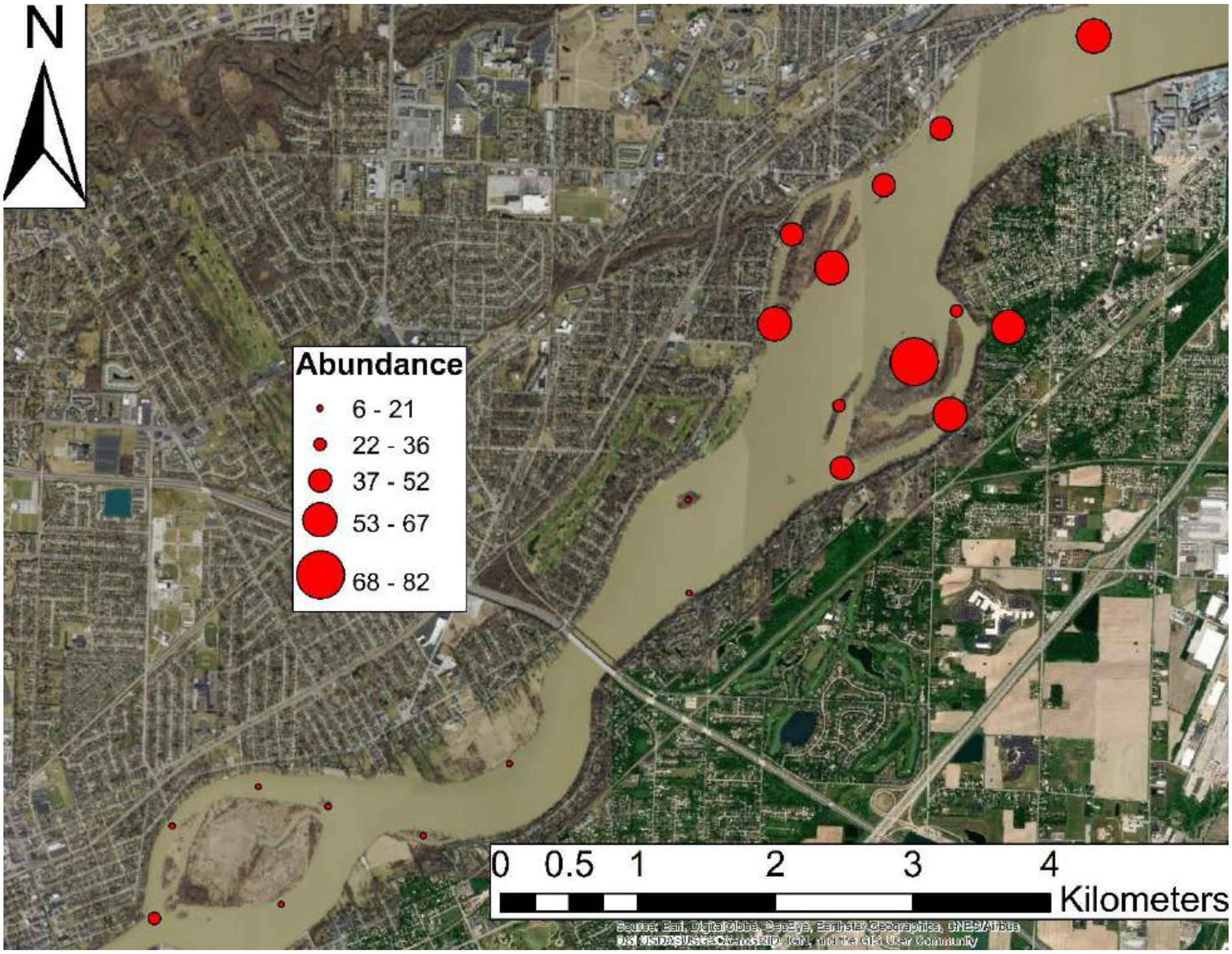


Figure 6. Linear regression of fish trawl species richness at each track against the average depth along that track. Black line is a fitted regression curve and red lines are 95% prediction intervals.

Electrofishing

The highest species richness, abundance, and IBI scores were generally located near the large island complexes (Figures 7-12). Fish abundances in August do not appear to follow this pattern, but there was a large catch of YOY gizzard shad which biased spatial patterns (Figure 8). Only one of the sites around Audubon generated high scores for richness and IBI, whereas in August all sites around this island had moderate to high scores for richness. Abiotic variables and shoreline type did not strongly influence species richness, abundance or IBI (Appendix B).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 7. July electrofishing abundance at each site. Abundances are totals across two transects at each site.

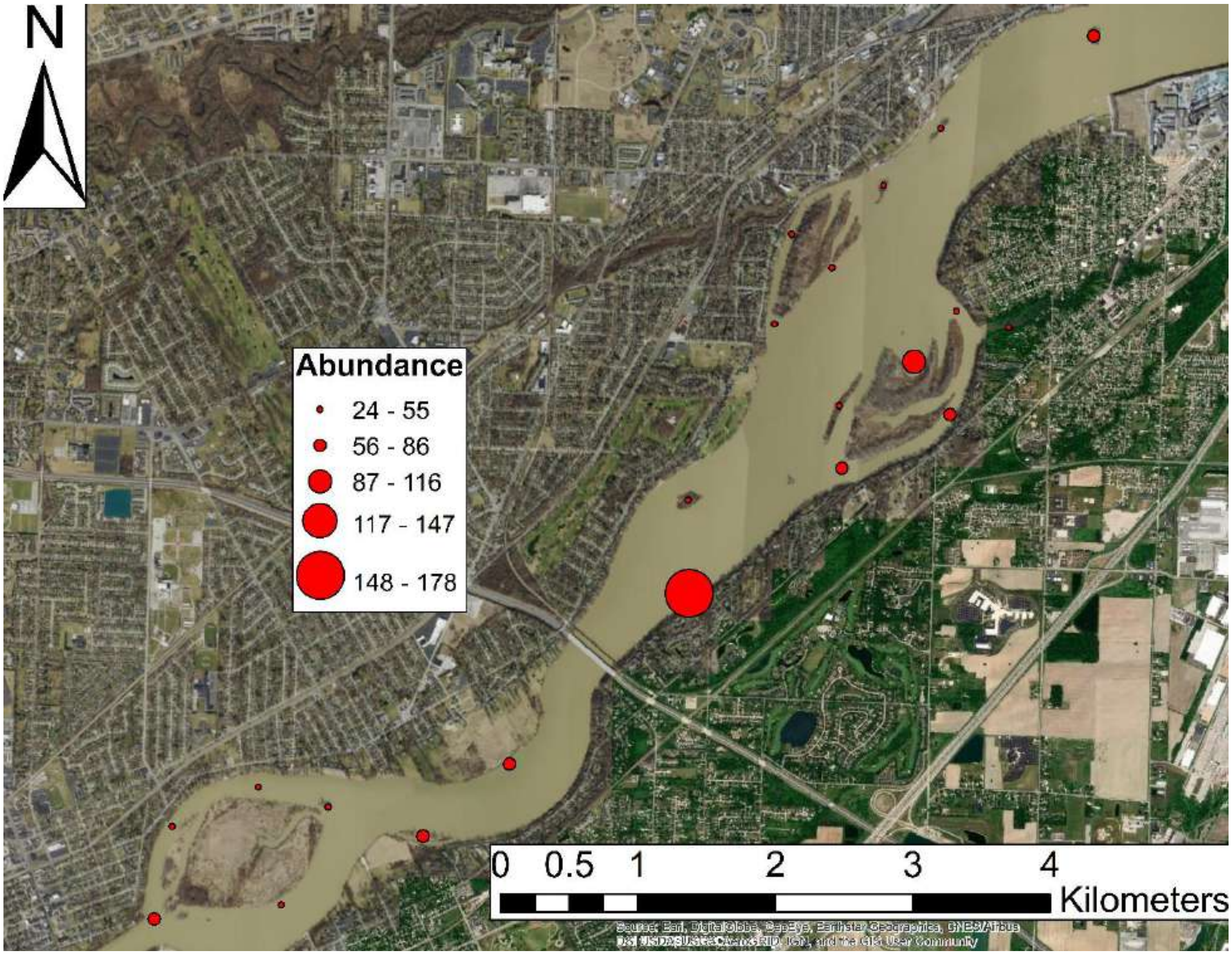


Figure 8. August electrofishing abundance at each site. Abundances are totals across two transects at each site.

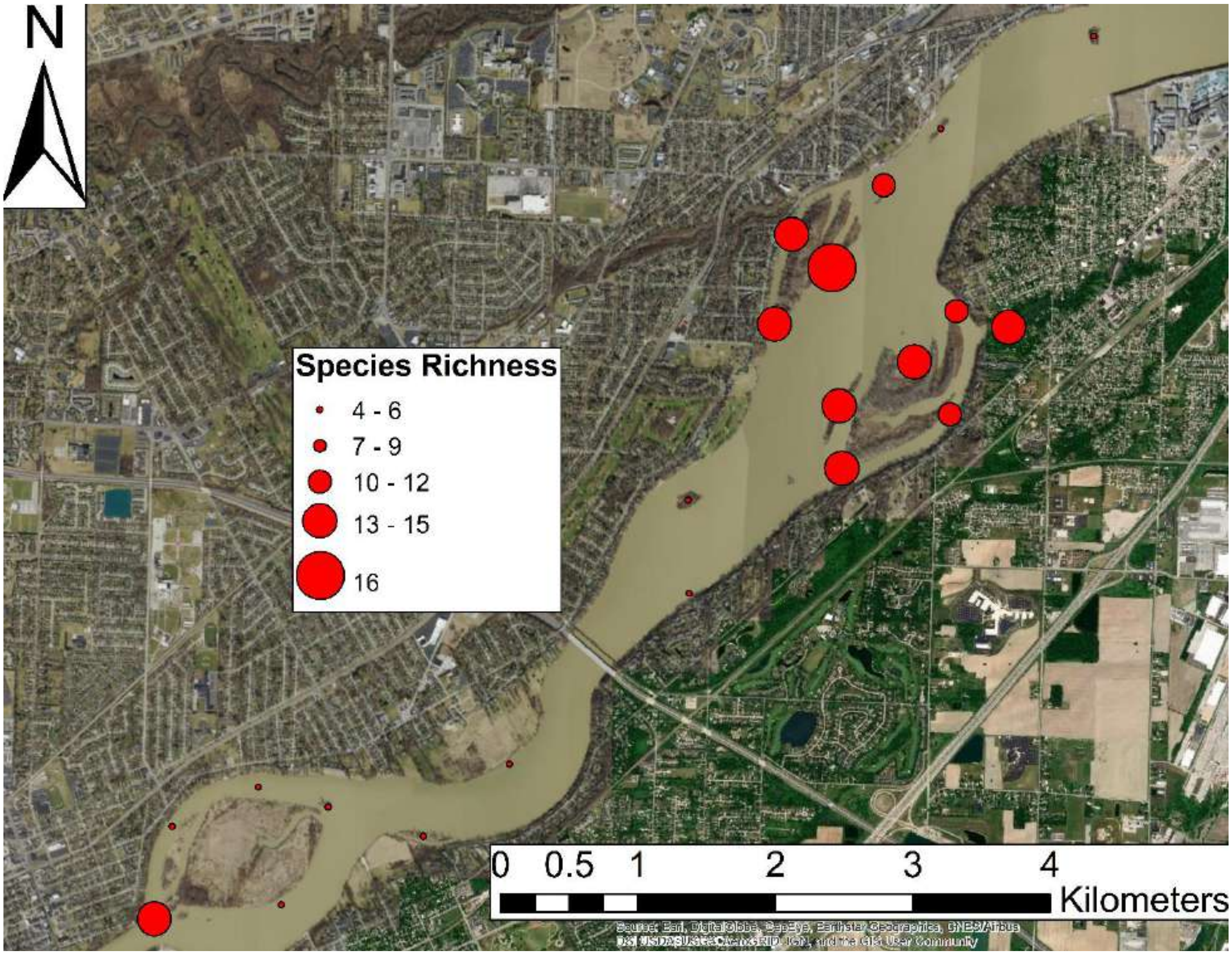


Figure 9. July electrofishing species richness at each site. Richness scores are overall scores across two transects.

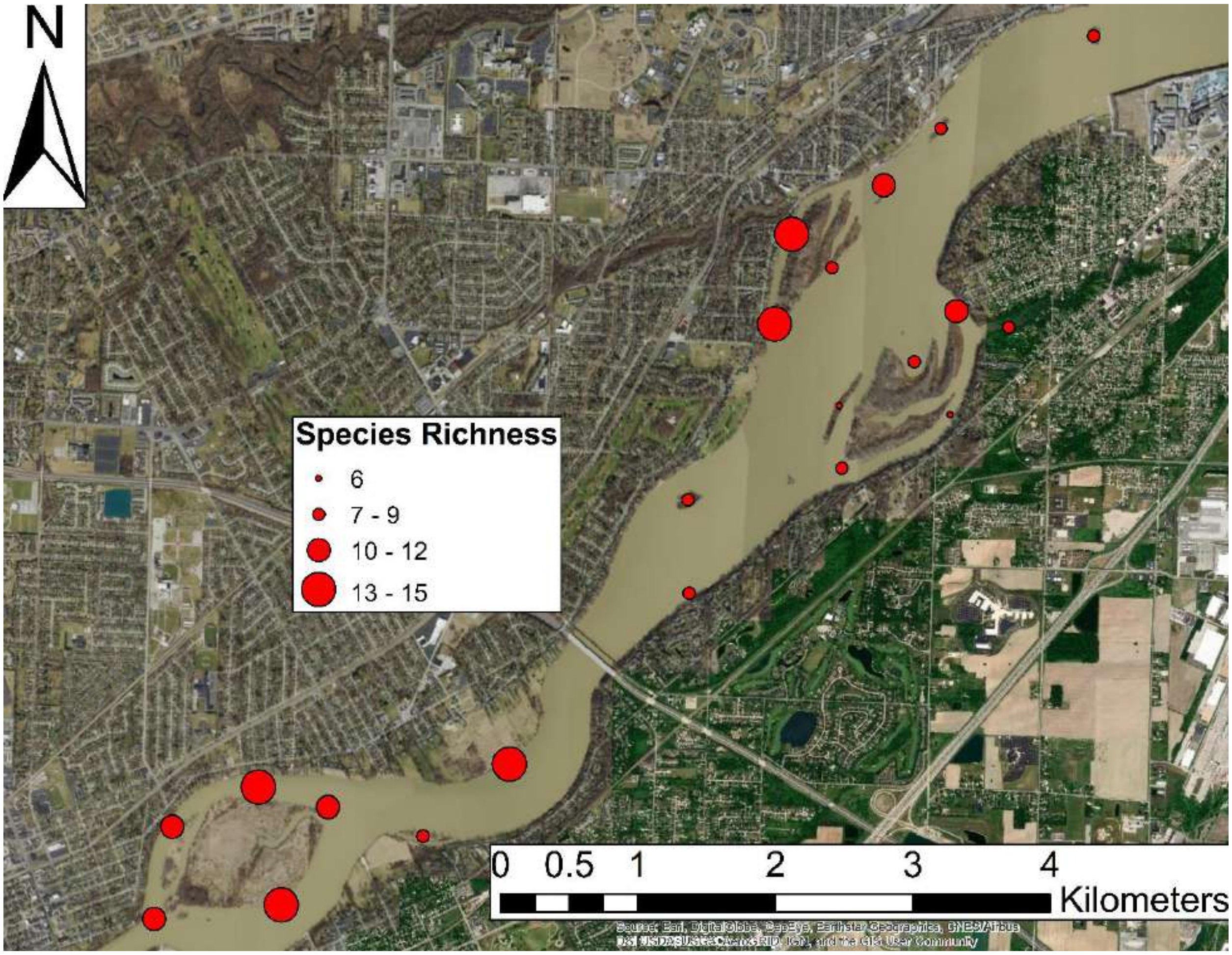


Figure 10. August electrofishing species richness at each site. Richness scores are overall scores across two transects.

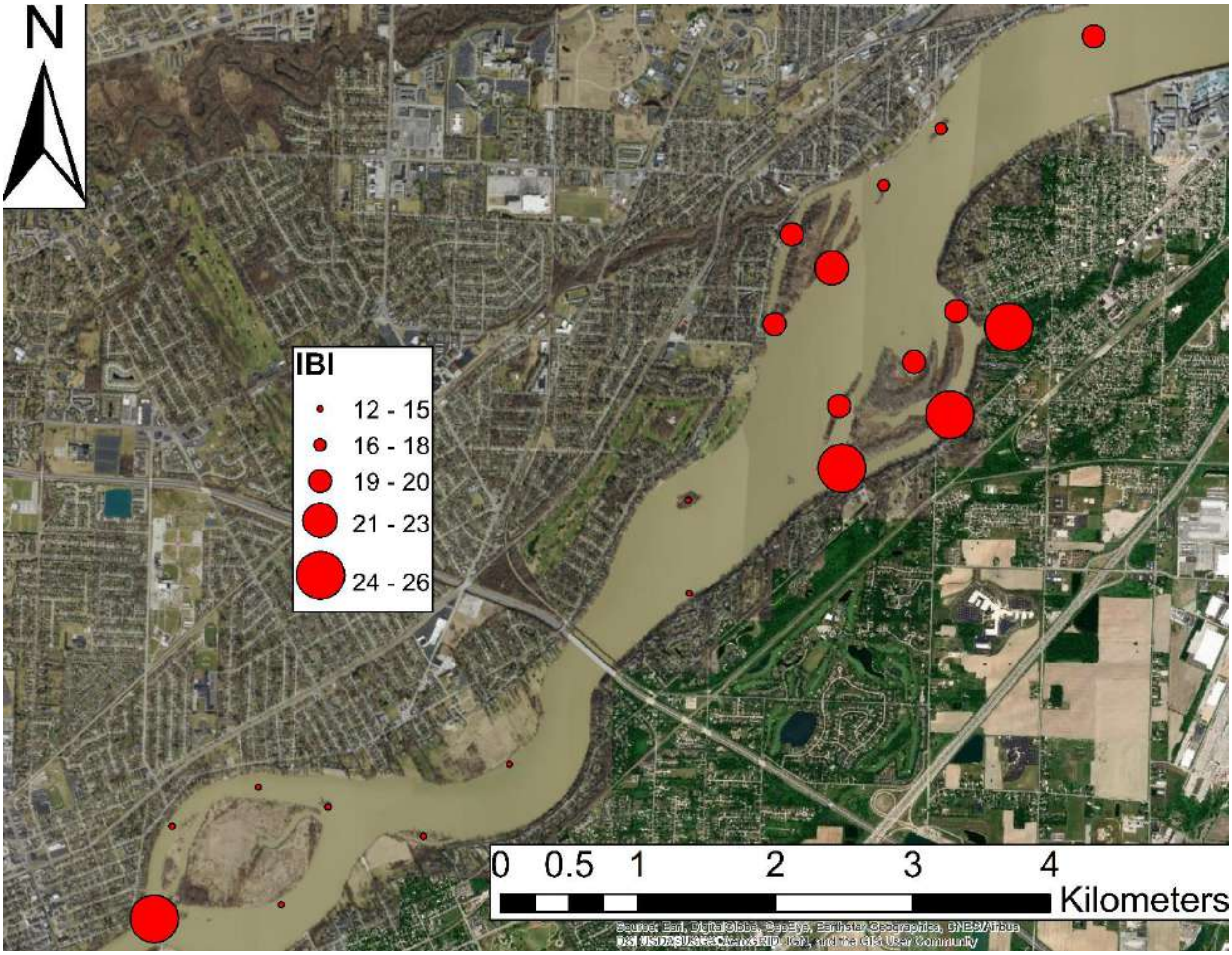
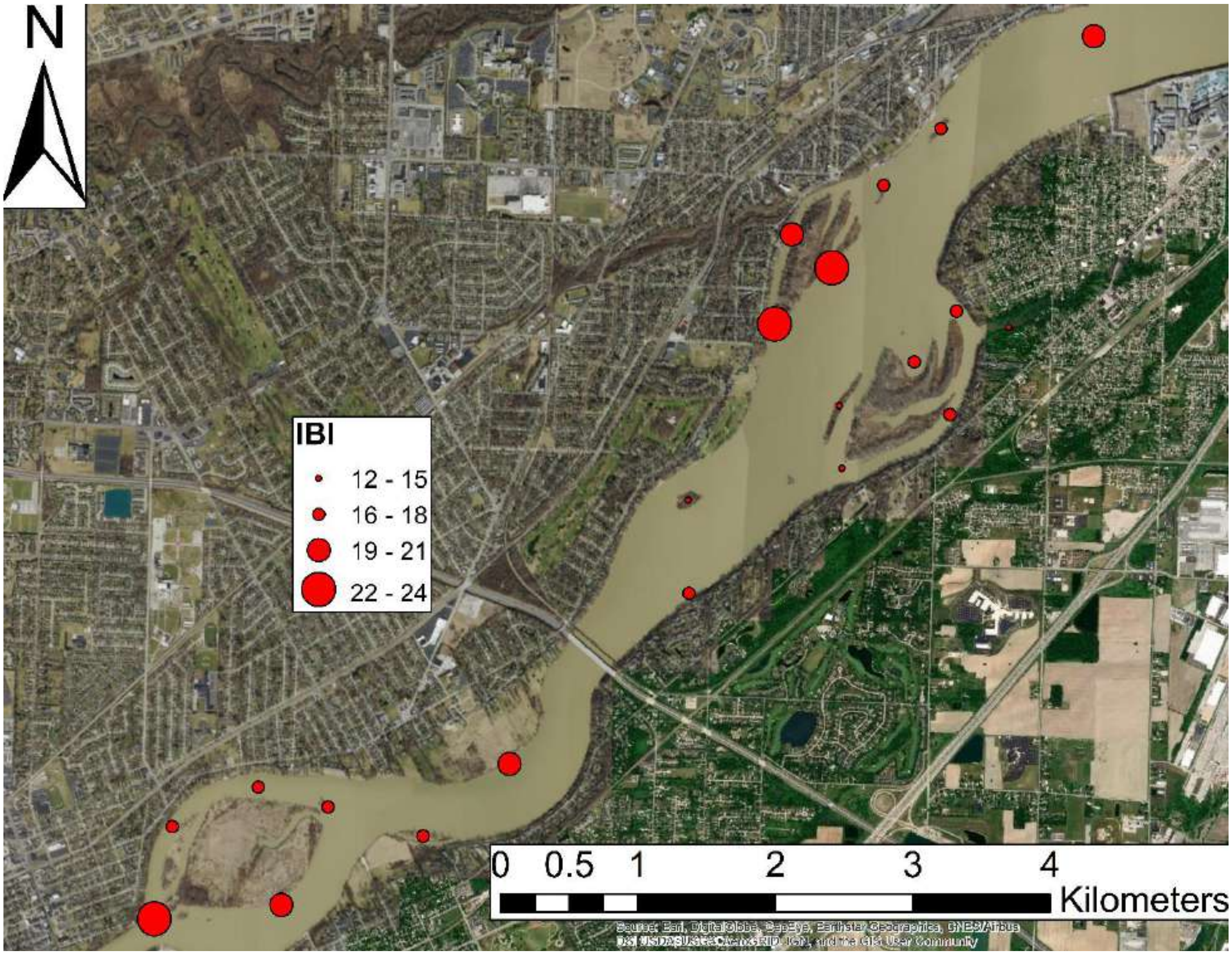


Figure 11. July electrofishing IBI scores at each site. IBI scores are overall scores across two transects.

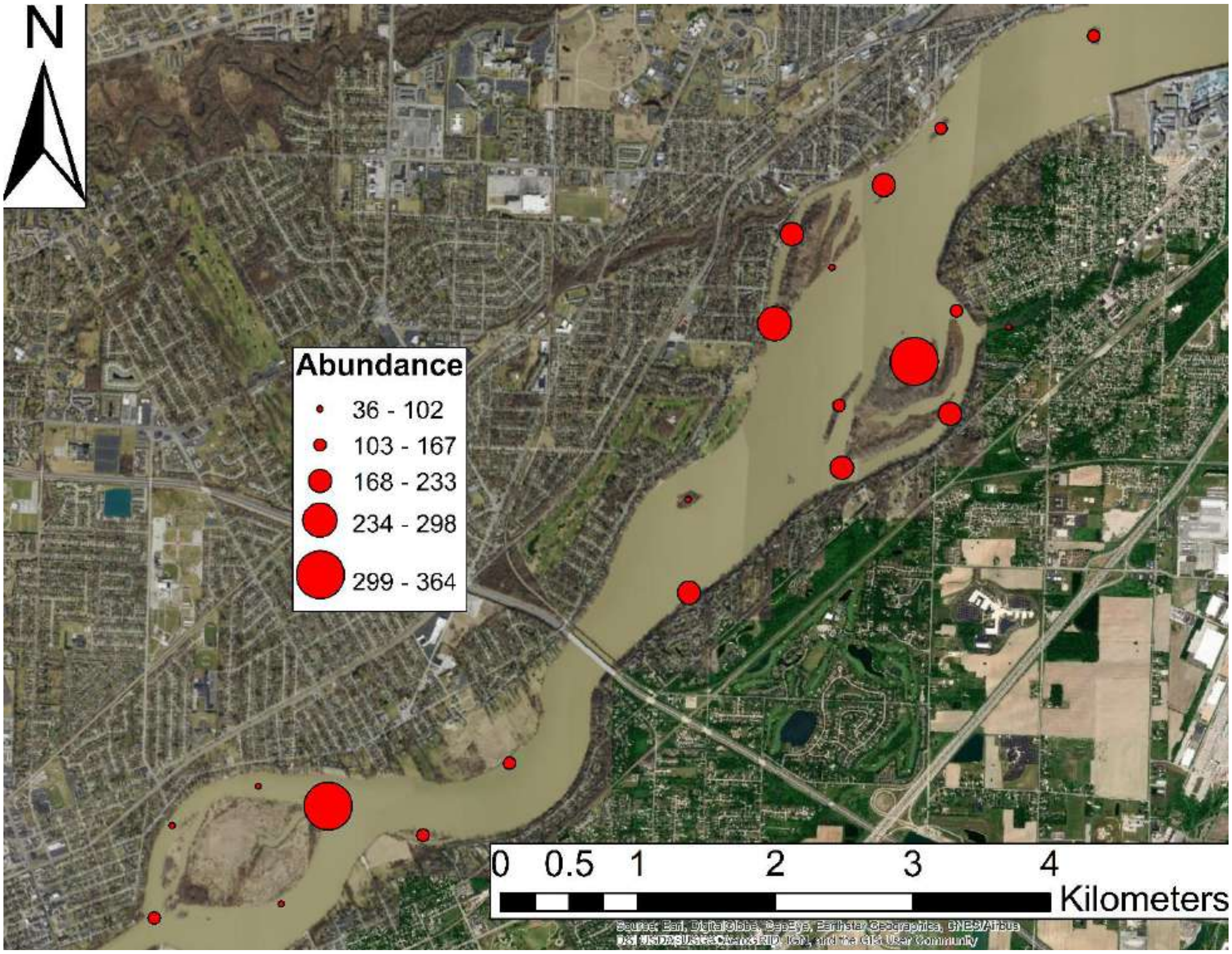


Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 12. August electrofishing IBI scores at each site. IBI scores are overall scores across two transects.

Fish catch overall patterns

When August electrofishing and fish trawl catch data are combined, the same overall patterns emerge. In general, the large island complexes appear to harbor the greatest abundances and species richness (Figures 13-14). In total, juvenile walleye were caught via either electrofishing or trawling at six of 21 sites (Figure 15).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 13. August electrofishing and fish trawl combined fish abundance at each site. Abundances are totals across all transects. Young-of-year channel catfish are not included as they were often caught by the hundreds and masked other spatial relationships.

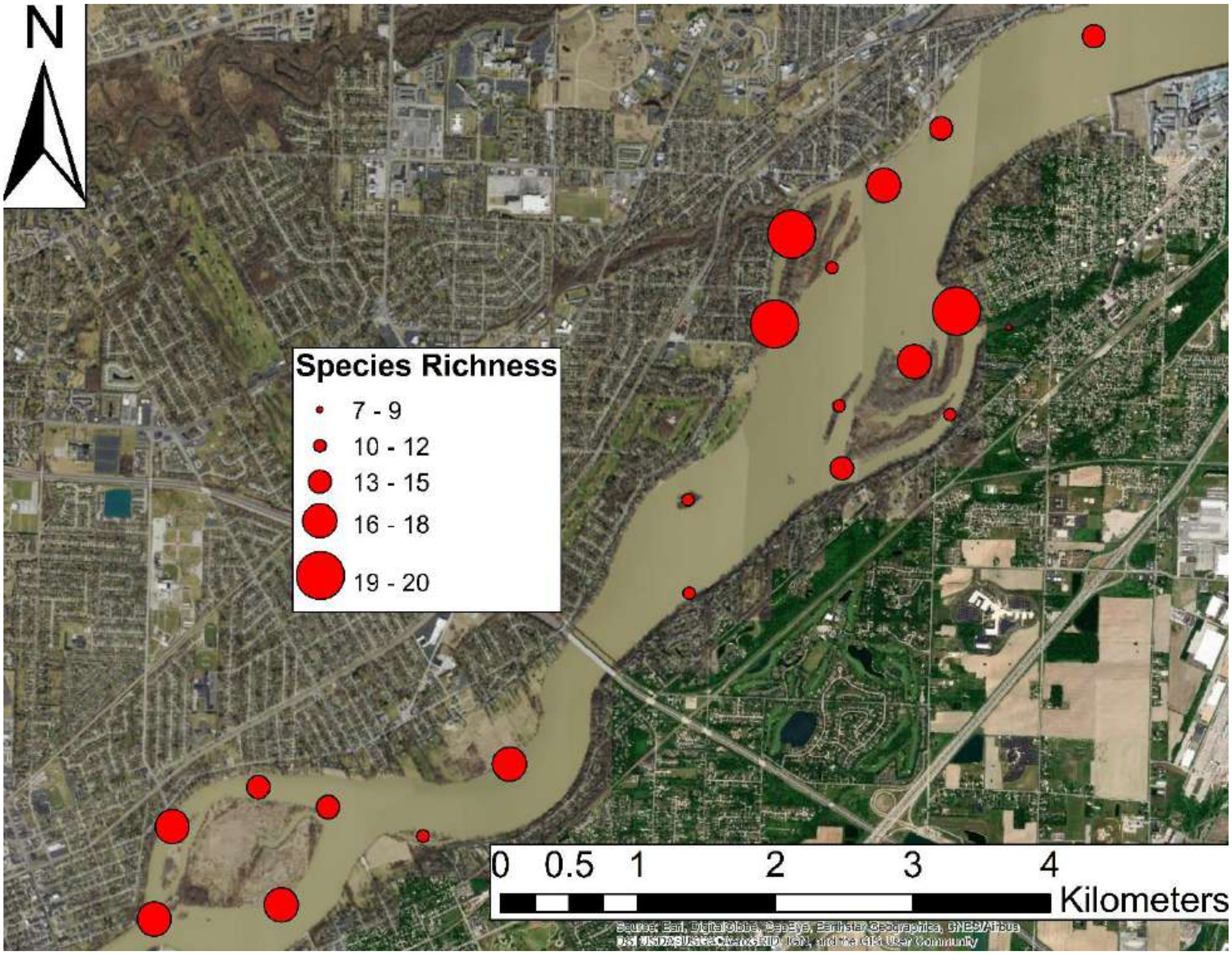


Figure 14. August electrofishing and fish trawl combined species richness. Richness scores are overall scores across all transects.

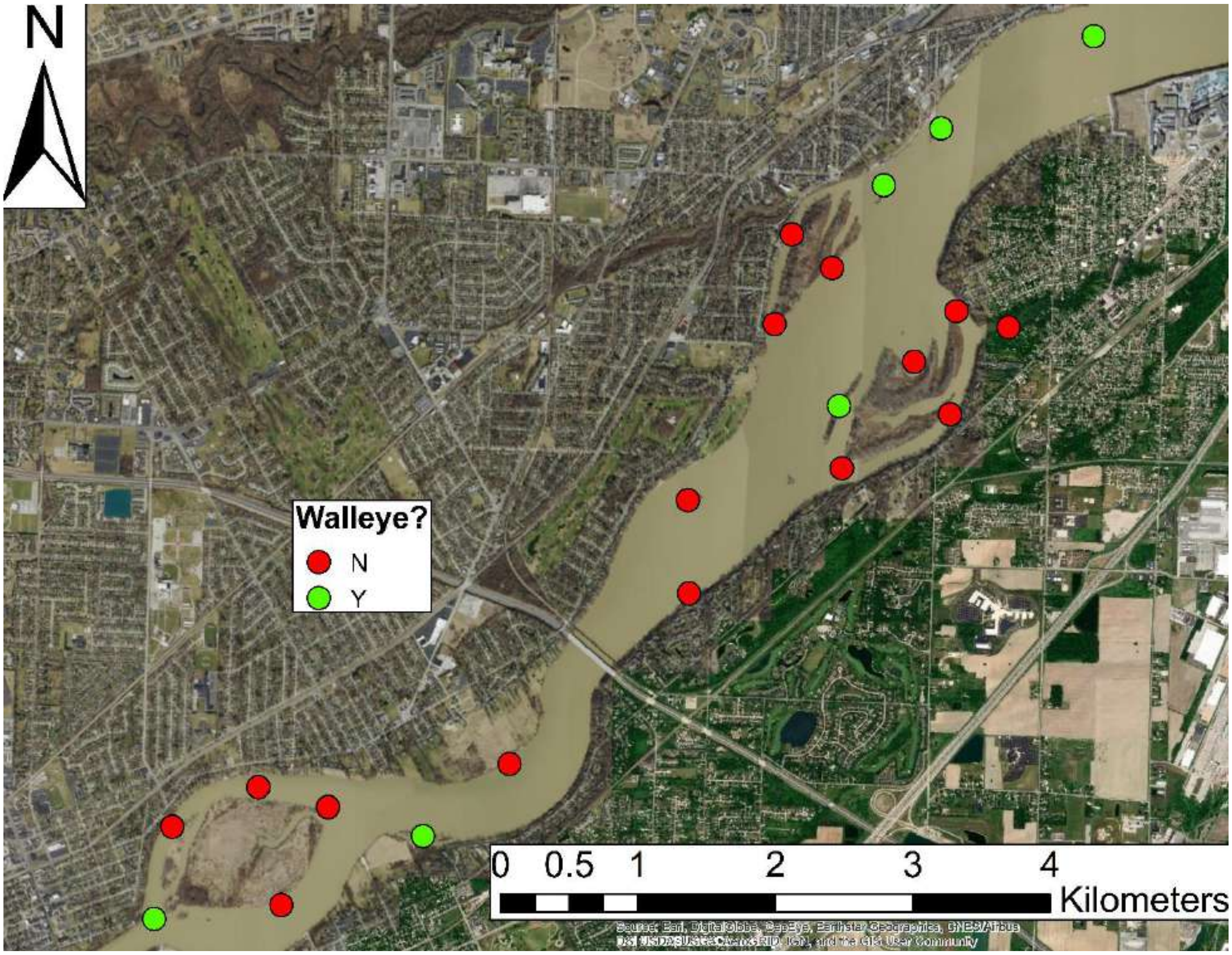
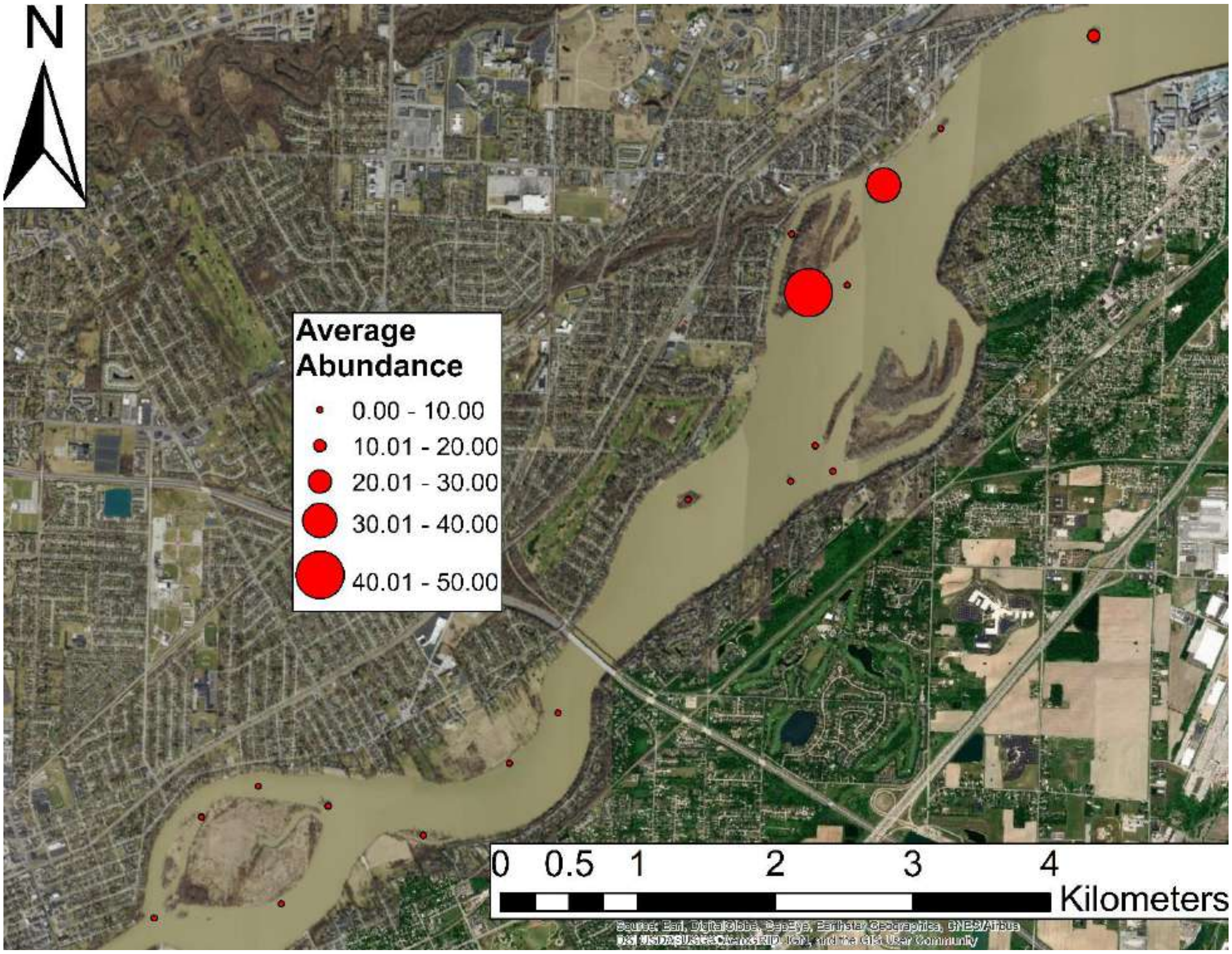


Figure 15. Presence of juvenile walleye for August electrofishing and fish trawl catch combined at each site.

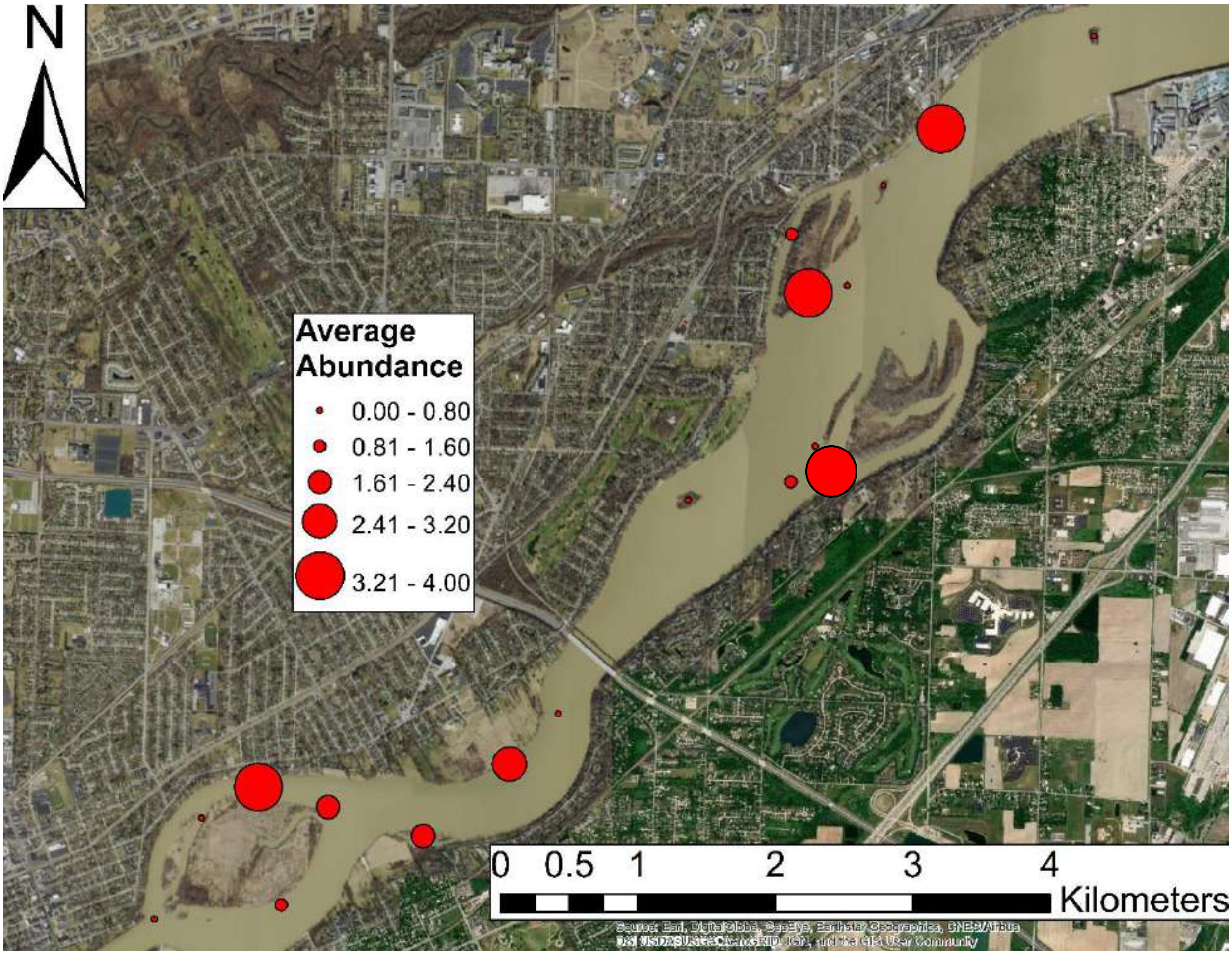
Unionid mussels

The locations of highest Unionid mussel richness and abundance were located around large island complexes (Figures 16-18). Specifically, the greatest hotspots in which both these metrics are high are near the upstream ends of Delaware and Grassy Islands. Abiotic variables and substrate did not appear to have a strong influence on the mussel catch data (Appendix B).



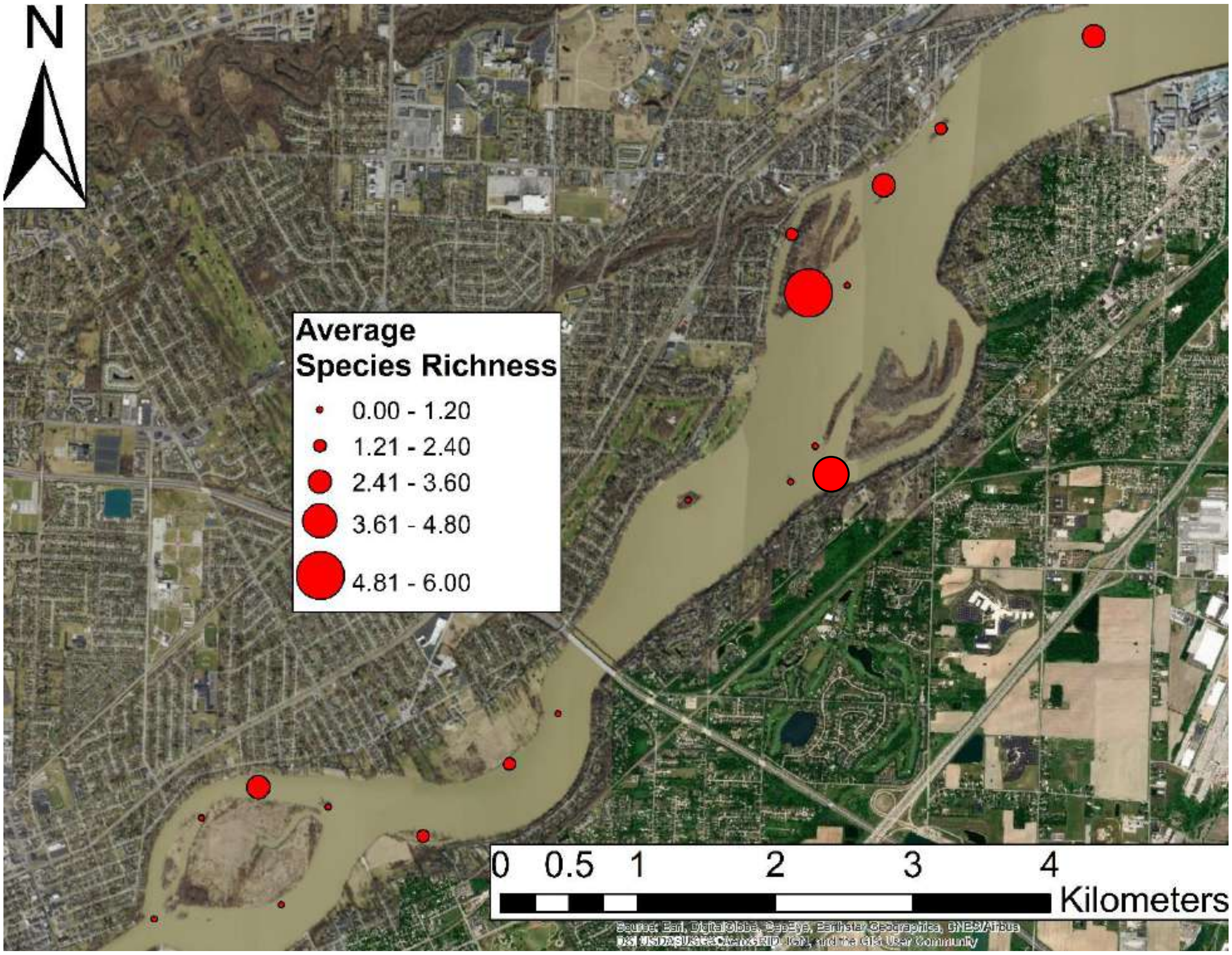
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 16. Unionid mussel abundance for individuals less than 10mm. Abundances are averages across all tracks.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 17. Unionid mussel abundance for individuals greater than 10mm. Abundances are averages across all tracks.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 18. Unionid mussel species richness at each site. Richness scores are averaged across all tracks.

Benthic invertebrates

Highest macroinvertebrate abundances on Hester Dendy samplers occurred around the Delaware/Horseshoe Island complex and Grassy Island (Figure 19). The majority of Hester Dendy sampler units where dominated by chironomid larva (Figure 20). At several sites where chironomid larvae were less predominant, samples consisted mostly of EPT taxa (Figure 21), almost all of which were caddisfly (Order *Trichoptera*) larvae (Figure 22). Mayflies (Order *Ephemeroptera*) were present on 12 of 31 sampling units, but no more than 10 were found on a sampler (Figure 23). No stoneflies (Order *Plecoptera*) were located on samplers. Taxa richness did not display any strong spatial patterns (Figure 24).

The 45 Ponar grab samples that were processed were almost exclusively dominated by oligochaetes and some chironomids, and were not utilized in establishing recommendations (Appendix C).

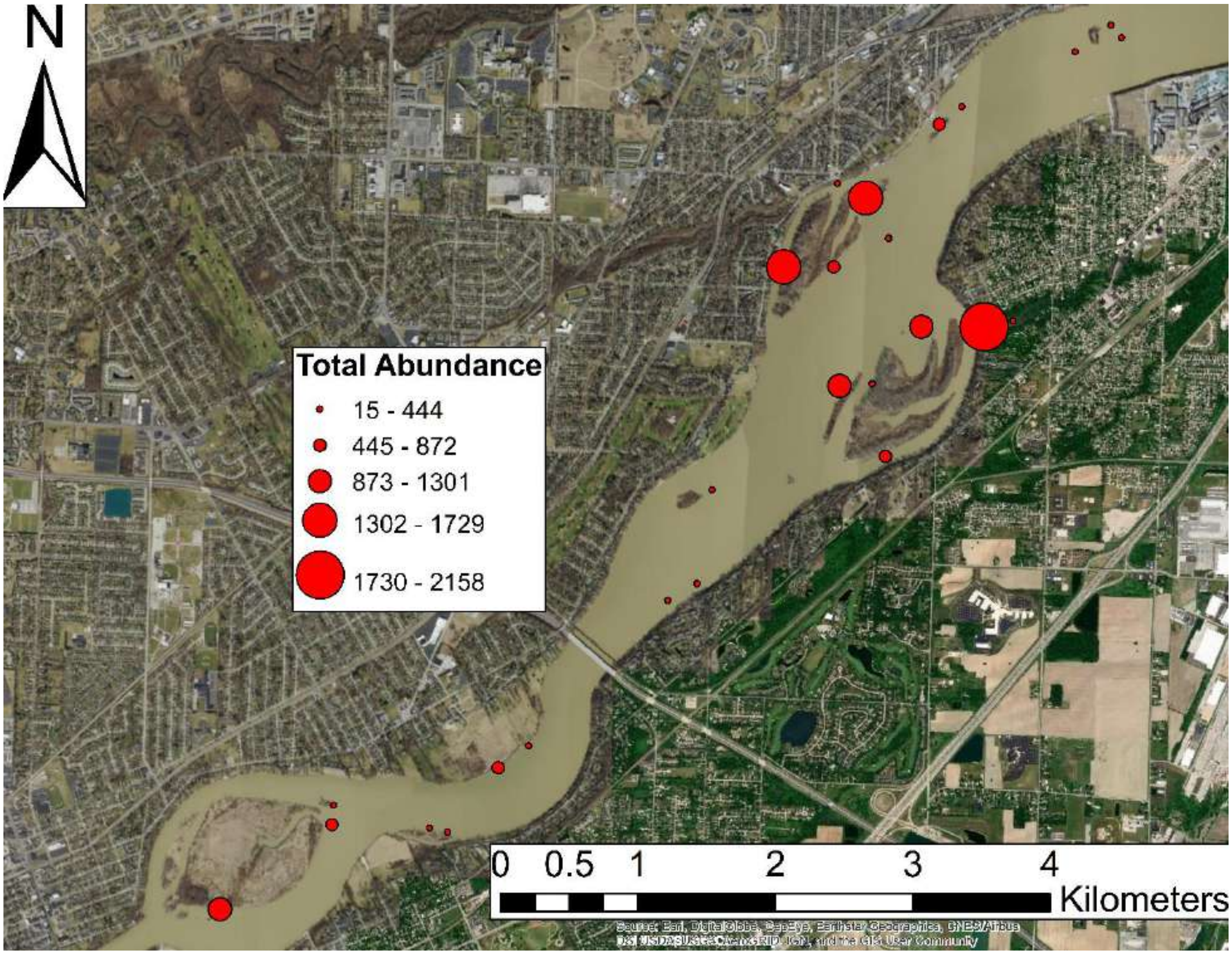


Figure 19. Total invertebrate abundance on Hester-Dendy sampling units (composite of three samplers).

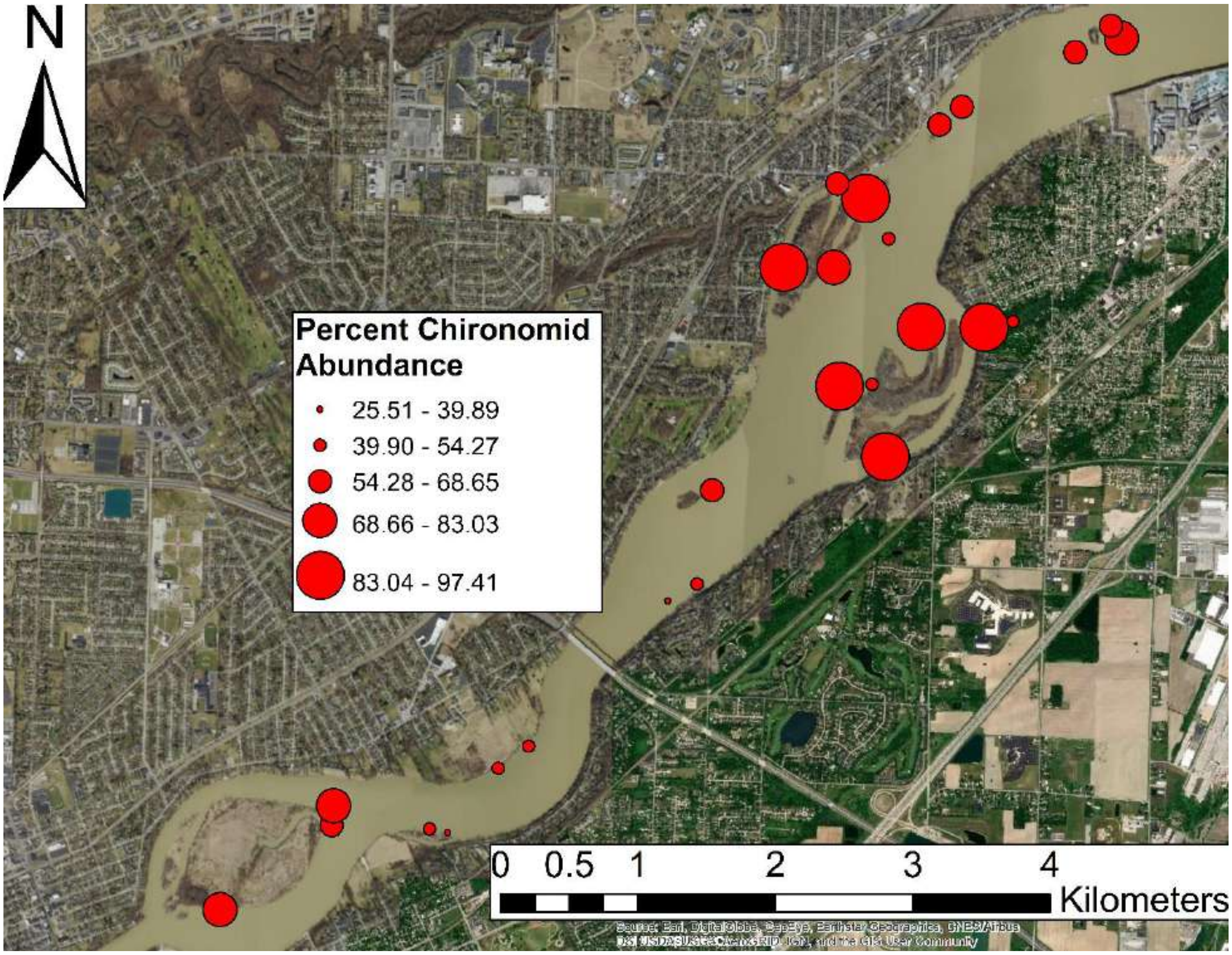
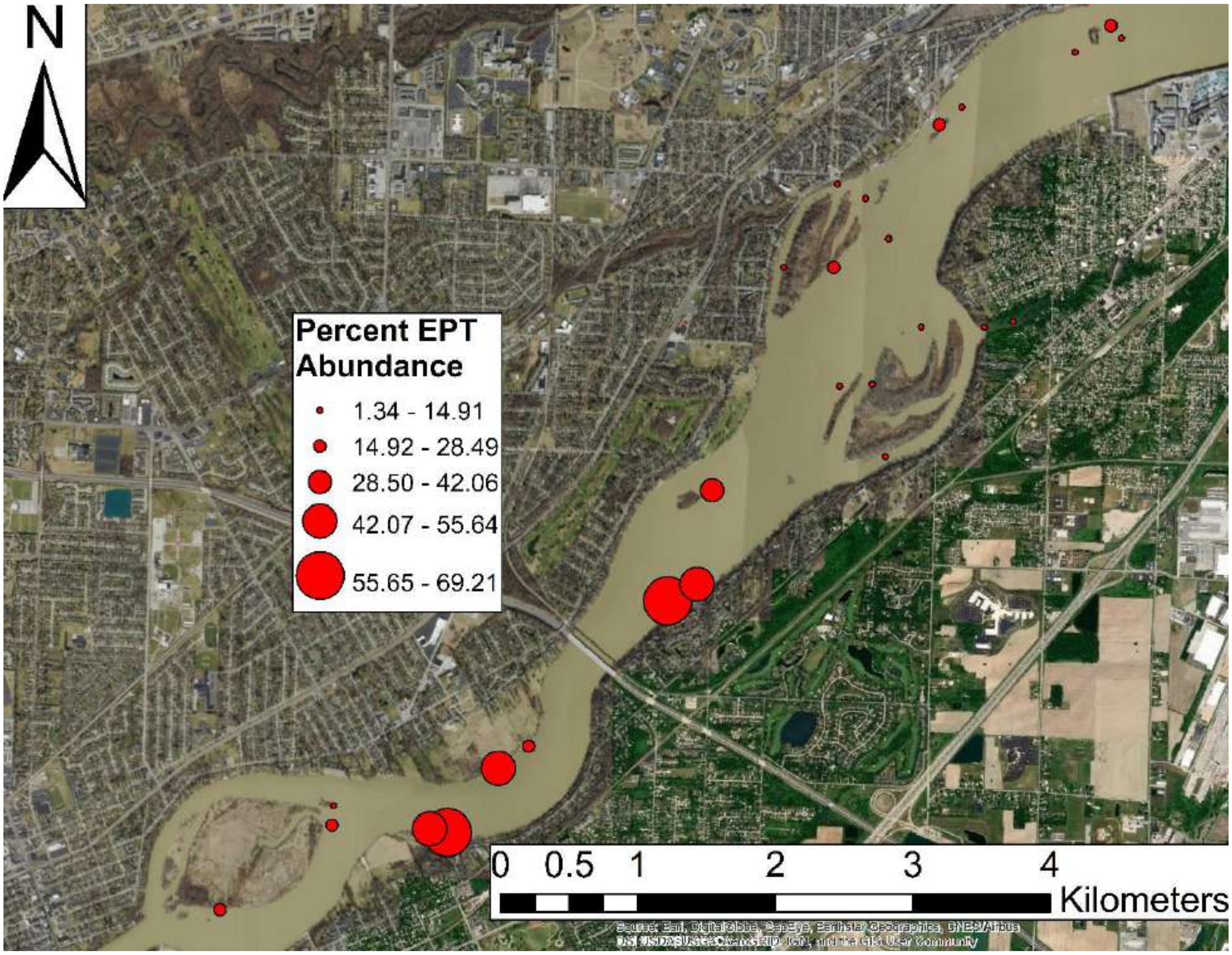


Figure 20. Percent chironomid abundance on Hester-Dendy sampling units (composite of three samplers).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 21. Percent EPT taxa (Ephemeraoptera, Plecoptera, Trichoptera) abundance on Hester-Dendy sampling units (composite of three samplers).

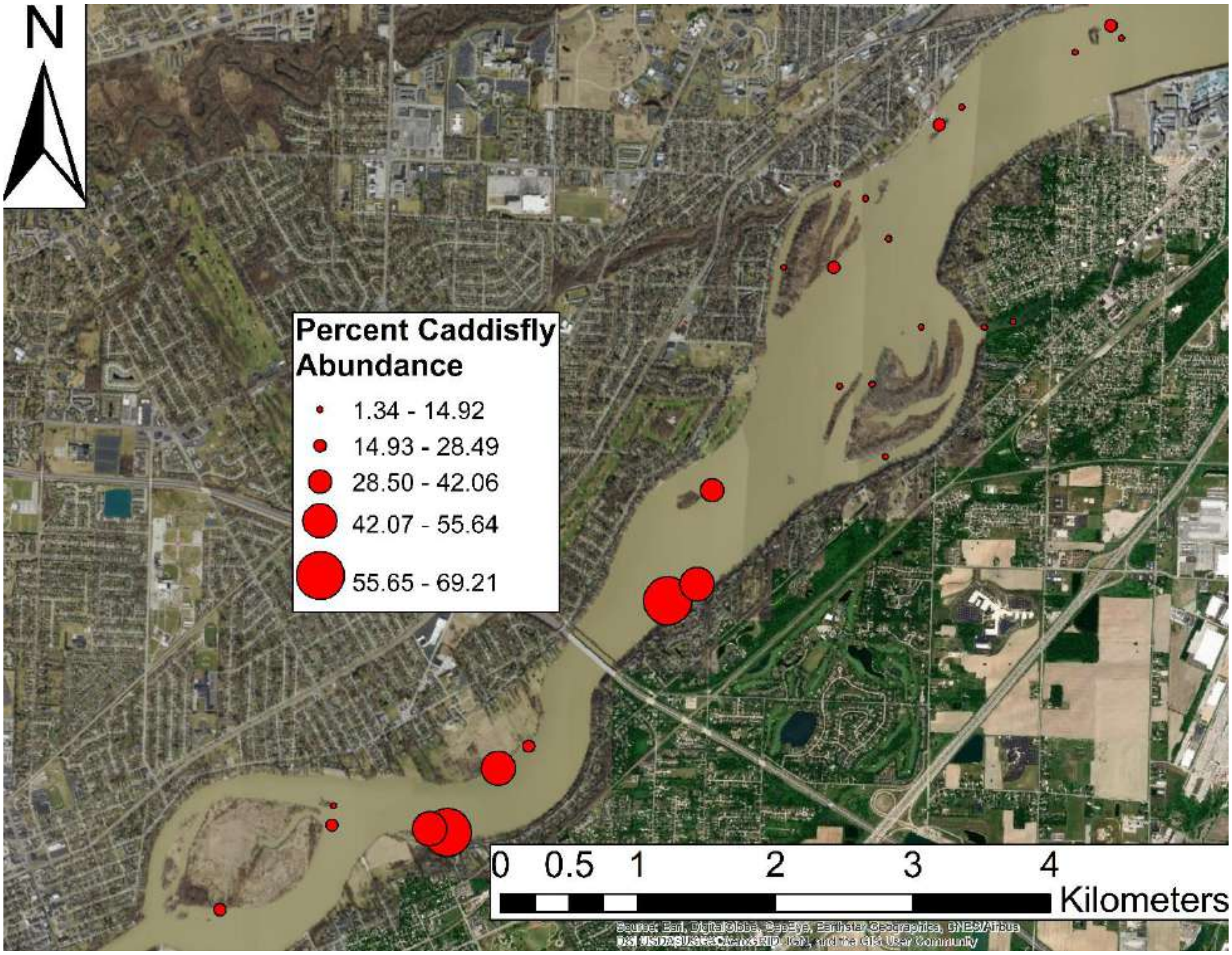


Figure 22. Percent caddisfly (Order: Trichoptera) abundance on Hester-Dendy sampling units (composite of three samplers).

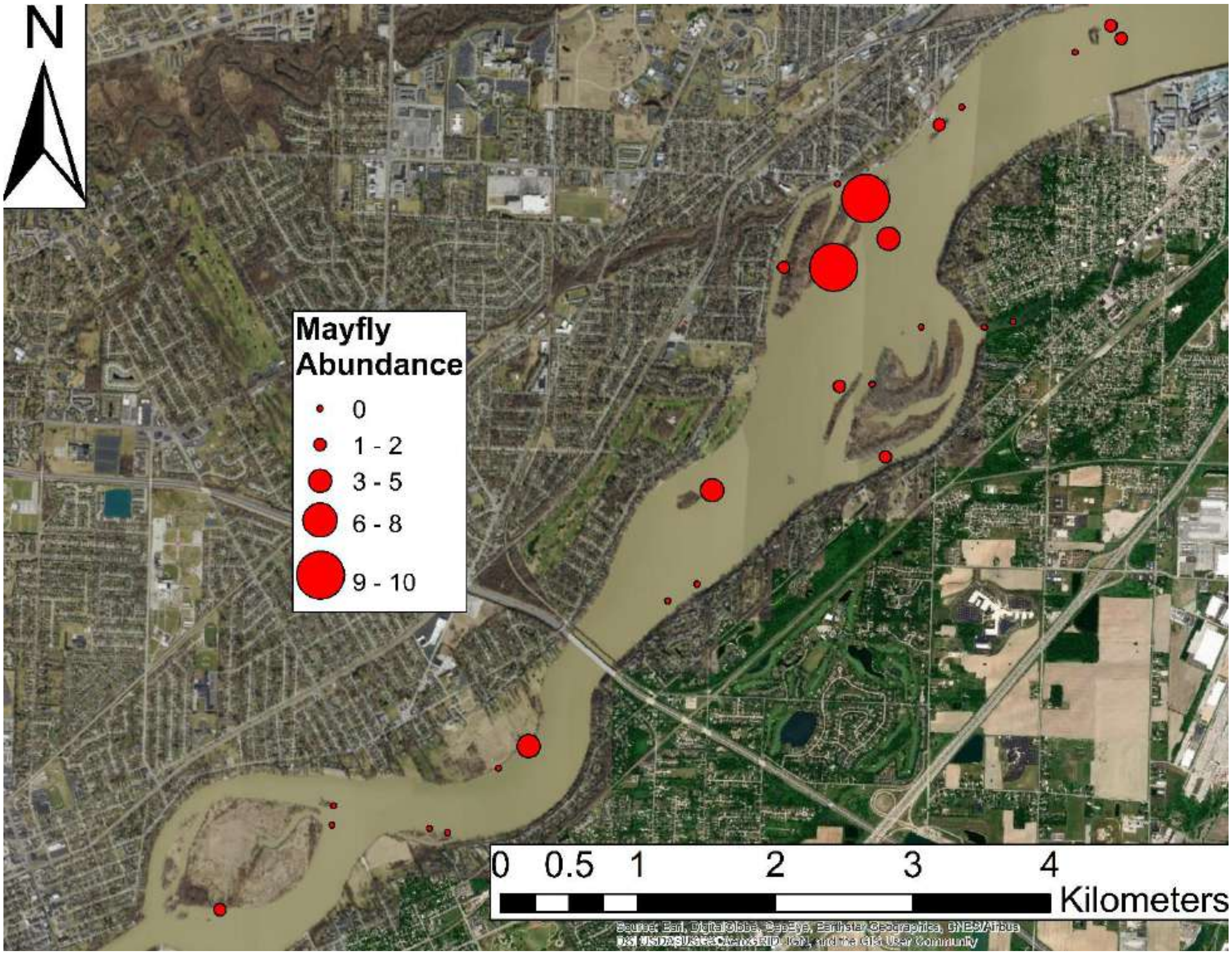


Figure 23. Mayfly (Order: Ephemeroptera) abundance on Hester-Dendy sampling units (composite of three samplers).

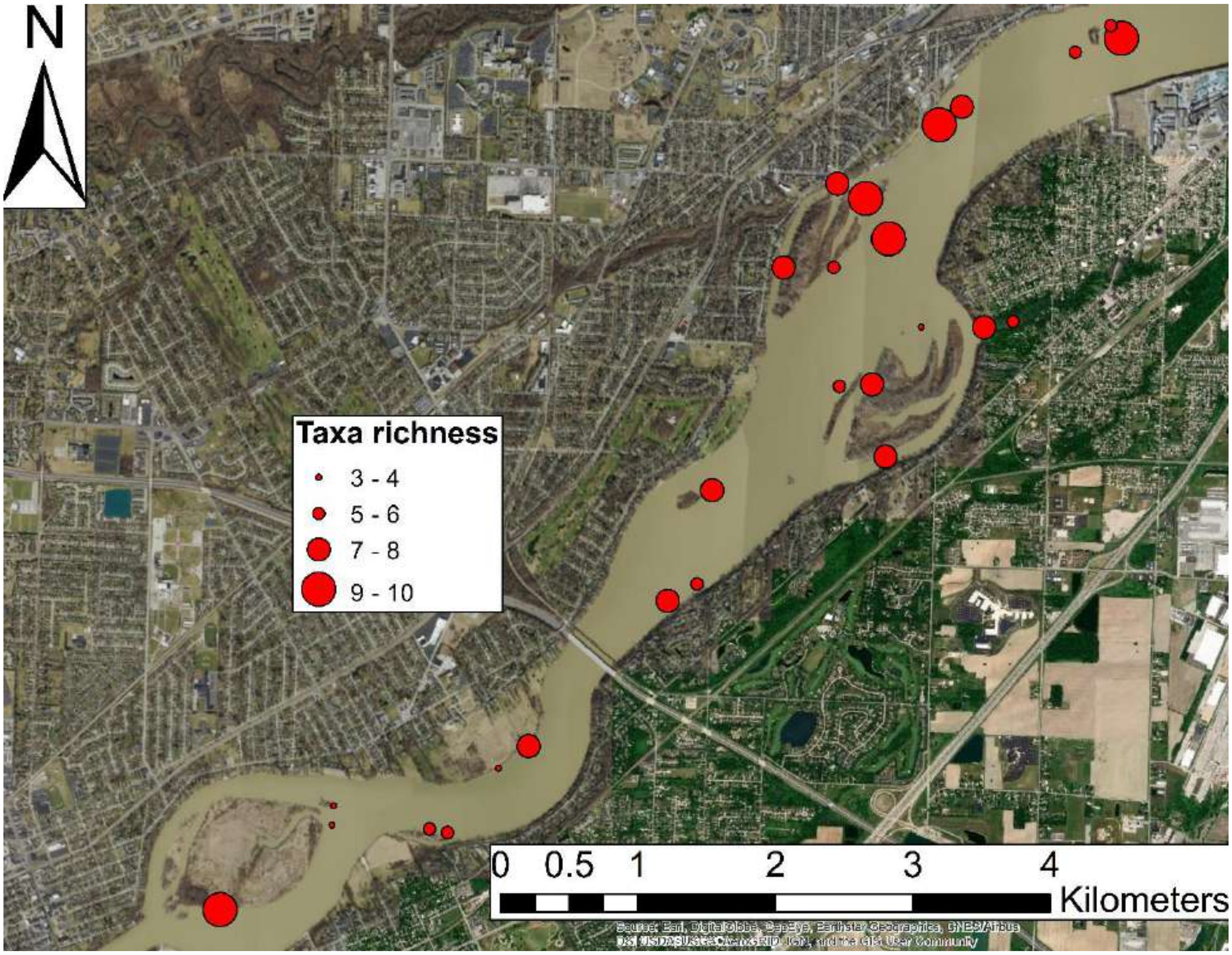


Figure 24. Taxa richness on Hester-Dendy sampling units (composite of three samplers). Note invertebrate ID was only taken to the order or family level.

Discussion & Restoration Recommendations

Although the spatial patterns and relationships with abiotic variables for the fish and invertebrate data were not particularly strong, in general, our results point to the importance of the large island complexes in the study reach. Sites with the highest richness and abundance across the sampled taxa were generally located around these complexes, and were lower near smaller islands or exposed main channel shoreline habitats. Species richness also appeared to increase in shallower waters for the fish trawl data, and since river island complexes generate these shallow water areas (Thorp 1992), they should appear to be the best opportunity for protection and enhancement of habitat in this reach.

In terms of actively restoring the degraded habitat in the Maumee River or enhancing existing higher quality habitat, a variety of features and structural improvements could potentially improve fish and invertebrate communities. For example, Sandheinrich and Atchison (1986) found that dikes, which are rock dams placed perpendicular to the shoreline (e.g. wing dikes) or in the main channel (e.g. chevron dikes) of rivers to modify flows, provide a range of depths, substrates, and flow conditions that increase habitat complexity and affect fish distributions and community diversity. Dikes provide useful and valuable habitat for a large variety of riverine fishes (Atwood 1997) and the fish communities associated with them are diverse, and may support more fish diversity than any other habitat within main channels (Jordan 2012). In the Upper Mississippi River for example, dikes and the areas protected from harsh flows behind dikes were providing habitat for invertebrates and fish in the Upper Mississippi in a study conducted by the US Army Corps of Engineers, St. Louis District (Jordan 2012). In the same study, diversity and taxonomic richness was higher on dikes than in the surrounding soft substrates in all three years of the study (Ecological Specialists, Inc. 1997). Wing dams in particular provide flow refugia and may support large concentrations of fish adapted to moderate flow (Jordan 2012). Chevron dikes also provide flow refugia, but also provide the added benefit of being able to aid in island development. Dredged material disposal within the chevrons can speed the island building process and provide a diversity of aquatic habitats associated with natural islands (Sohngen et al. 2008).

River island complexes provide a variety of different habitat types and increase habitat heterogeneity of the system (Johnson and Jennings 1998), and have been shown to have a significant positive effect on both density and diversity of benthic invertebrates (Thorp 1992) and fish species (Chipps et al. 1997). Islands interrupt the deepwater regions of rivers by providing shallow water habitat similar to the littoral zone (Thorp 1992). The shallow backwaters or side channels created by them provide refuge from high currents, particularly those generated at thalwegs (Fremling et al. 1989, Barko and Herzog 2003). They provide a variety of other depth and flow conditions that can satisfy the preferences of various aquatic species. In the Mississippi River, for example, Pallid sturgeon (*Scaphirhynchus albus*) has been shown to select island tip habitat disproportionately to its availability (Hurley et al. 2004). In another study of Pallid and Shovelnose Sturgeon habitat use in the Mississippi River, among ten habitat types present in the study reach, sturgeon CPUE at the downstream tips of islands in particular were nearly double that of other habitat types (Hintz et al. 2016). Additionally, vegetation which is sheltered on the shoreward side of alluvial islands has also been shown to be positively correlated with fish density (Johnson and Jennings 1998). Furthermore, islands can even support fish communities which are distinct from the communities supported from conventional dike fields which do not contain or create island habitats (Allen 2010). Overall, due to the physical and biological complexity they bring to a river corridor, the presence of island complexes can be used as an ecosystem-level indicator of the biological health of a river (Tockner 2007).

Course woody debris are another important habitat structure that has been shown to benefit fish and invertebrate populations. Woody debris provide cover and create unique hydrological features such as pools and backwaters that fish have been shown to utilize in a variety of studies (Harmon et al. 2006). They have also been known and are used to stabilize shorelines and preferred spawning habitat for some fishes. For example, woody debris prevent spawning-sized gravel that accumulates upstream of it from being flushed downstream (Opperman 2006). Woody debris are also an important habitat resource for macroinvertebrates, which use them as a source of food or substrate (Thorp 1992; Pitt and Batzer 2011). Some macroinvertebrates can directly consume wood (xylophagy; Anderson et al. 1978, Hoffman and Hering 2000) or feed on the biofilms (bacteria, fungi, algae) that develop on wood surfaces (Johnson et al. 2003, Spanoff et al. 2006, Eggert and Wallace 2007). Given the prevalence of macroinvertebrates, woody debris become important feeding zones for juvenile and smaller fish that feed on these invertebrates.

Another habitat feature that if generated directly or indirectly from restoration activities is submerged aquatic vegetation (SAV). SAV serves as nursery habitat for juvenile fish by providing prey resources and protection (Boesch and Turner 1984; Werner and Gilliam 1984; Kahn and Kemp 1985; Peterson 2003). For example, juvenile sturgeon abundance increased with proportion of submerged vegetated habitat near two islands in the middle Mississippi River (Hintz et al. 2015). Study of fish communities in Maumee Bay also found greater fish species richness in SAV beds (Miller et al. 2018). Similarly to woody debris areas, macroinvertebrates also utilize SAV as either a direct or indirect food source, as a source of habitat, as well as refuge from predators (e.g. fish) (Chaplin and Valentine 2009; Valinoti et al. 2011). They have been shown to have success utilizing both native and exotic submerged aquatic vegetation (Chaplin and Valentine 2009; Valinoti et al. 2011). Macroinvertebrate production on exotic SAV has been shown to exceed that of production on native SAV in some cases, but this is likely attributable to the structure of the exotic vegetation which may reduce predator feeding efficiency considerably, thus making this increased production inaccessible to the rest of the ecosystem (Chaplin and Valentine 2009). Thus, native submerged aquatic vegetation would be most beneficial for the ecosystem as it may address the needs of multiple trophic levels. Due to sensitivity to high flows though (Sohngen et al. 2008), if SAV growth is meant to be promoted as a means of restoration, this must occur in river areas that are shielded from these conditions. Wave action in a heavy use river can make this difficult, but structures such as woody palisades can be used successfully as wave breakers in these systems (Boedeltje et al. 2001).

Project sites and specific recommendations

The following recommendations are meant to augment and protect habitat in the lower Maumee River from the Audubon Islands downstream to the Rt. 75 bridge for the benefit of fish and invertebrate species. These recommendations are based on a combination of fish and invertebrate catch data and habitat data collected in summer 2019, existing knowledge of the Maumee's fluvial processes and historical conditions, and literature review of other restoration activities and habitat types which can benefit these communities as outlined above. In general, the preservation and creation of large islands in the main channel in this reach of the Maumee will aid in the increase in biotic index scores. We suggest the installation of structures such as rip rap dikes (wing or chevron) to aid in the accretion of sediments around existing island complexes and for creation of new island complexes, promotion of SAV growth in island coves, native vegetation plantings, and installation of woody debris near sites severally lacking in potential structure/cover for fish. Below, we give specific recommendations for each site which are displayed across four maps, and the priority of each project has been ranked. Prioritization for each project is based on a combination of anticipated effort/cost (none, low, moderate, high), confidence of success in increasing biotic index scores (low, moderate, high), the need for a particular project based on the ecological state of the project site (low, moderate, high) and the likelihood of unintended impacts on fluvial processes that could have negative ecosystem effects (none, low, moderate, high). The projects are scored relative to the other projects – for example, if the need for a project is ranked as "low", it does not necessarily mean it is unimportant, it means it is simply less important than other projects being considered. Each qualitative metric score had a corresponding numerical score (e.g. for anticipated effort, numerical scores were as follows: none = 1, low = 2, moderate = 3, high = 4). The sum of these numerical scores determined priority ranking. In cases in which the sum was equivalent across two or more project sites, the scores for need and success confidence took precedence.

Table 1. Segment 1 (Audubon Islands to Turnpike bridge) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
1	- juvenile walleye captured in trawls - known walleye spawning ground - July and August electrofishing IBI score was one of the highest	*Protection* - Avoid changes to flow or structures around island	- walleye spawning area preservation	none	high	none	high	**1**
2	- shoreline classification indicated lack of habitat complexity - shoreline lacked vegetation to support shoreline structural integrity - low total fish abundance across August sampling methods - low total fish abundance and	- Install root wads, submerged trees/logs, or other woody debris along bare shorelines - Plant native vegetation along bare shorelines	- Fish/invertebrate habitat augmentation - bank stabilization	low	high	low	moderate	**9**

	richness for July electrofishing - low Unionid mussel abundance and richness							
3	- shallow cove environment and protection from harsh flows could help generate SAV - low total fish abundance and richness for July electrofishing near mouth of cove - low July and low August IBI near mouth of cove - low percent EPT abundance and invertebrate taxa richness on Hester-	- Install rip rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	low	moderate	**12**

	Dendies near mouth of cove							
4	- shoreline classification indicated lack of habitat complexity - shoreline lacked vegetation to support shoreline structural integrity - low total fish abundance across August sampling methods - low total fish abundance and richness for July electrofishing - low July and moderately low August IBI	- Install root wads, submerged trees/logs, or other woody debris along bare shorelines - Plant native vegetation along bare shorelines	- Fish/invertebrate habitat augmentation - bank stabilization	low	high	low	moderate	**8**

5	- shoreline classification indicated lack of habitat complexity - shoreline lacked vegetation to support shoreline structural integrity - low total fish abundance across August sampling methods - low total fish abundance and richness for July electrofishing	- Install root wads, submerged trees/logs, or other woody debris along bare shorelines - Plant native vegetation along bare shorelines	- Fish/invertebrate habitat augmentation - bank stabilization	low	high	low	moderate	**7**
6	- high Unionid mussel species richness	*Protection* - Avoid changes to flow or structures around island	- mussel bed preservation	none	high	none	high	**5**
7	- fish species richness high for August electrofishing despite exposed shoreline - low total fish abundance across	Install rip-rap wing-dikes along exposed shoreline	- Fish/invertebrate habitat augmentation	moderate	moderate	moderate	low	**13**

	August sampling methods - low total fish abundance and richness for July electrofishing - low Unionid mussel richness							

Figure 25. Segment 1 of study reach with project sites labeled.

Table 2. Segment 2 (Turnpike bridge to exposed shoreline downstream of Marengo Island) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
8	- high August total fish abundance (gizzard shad dominated), but low richness across August sampling methods - low total fish abundance and richness for July electrofishing - low July and August IBI - shoreline classification indicated lack of habitat complexity	Install root wads, submerged trees/logs, or other woody debris along bare shorelines	- Fish/invertebrate habitat augmentation	low	high	low	moderate	**10**
9	- low total fish abundance and richness across August sampling methods	Install chevron-style rip-rap dike at upstream end of island	- sediment accretion/island growth	high	low	high	high	**16**

	- low total fish abundance and richness for July electrofishing - low July and August IBI - low Unionid mussel abundance and richness - small island, lacks protection from flows							
10	- not sampled, but has no protection from flows which may impact fish and invertebrate communities	Install rip-rap wing-dikes along exposed shoreline	- Fish/invertebrate habitat augmentation	moderate	low	high	moderate	**19**

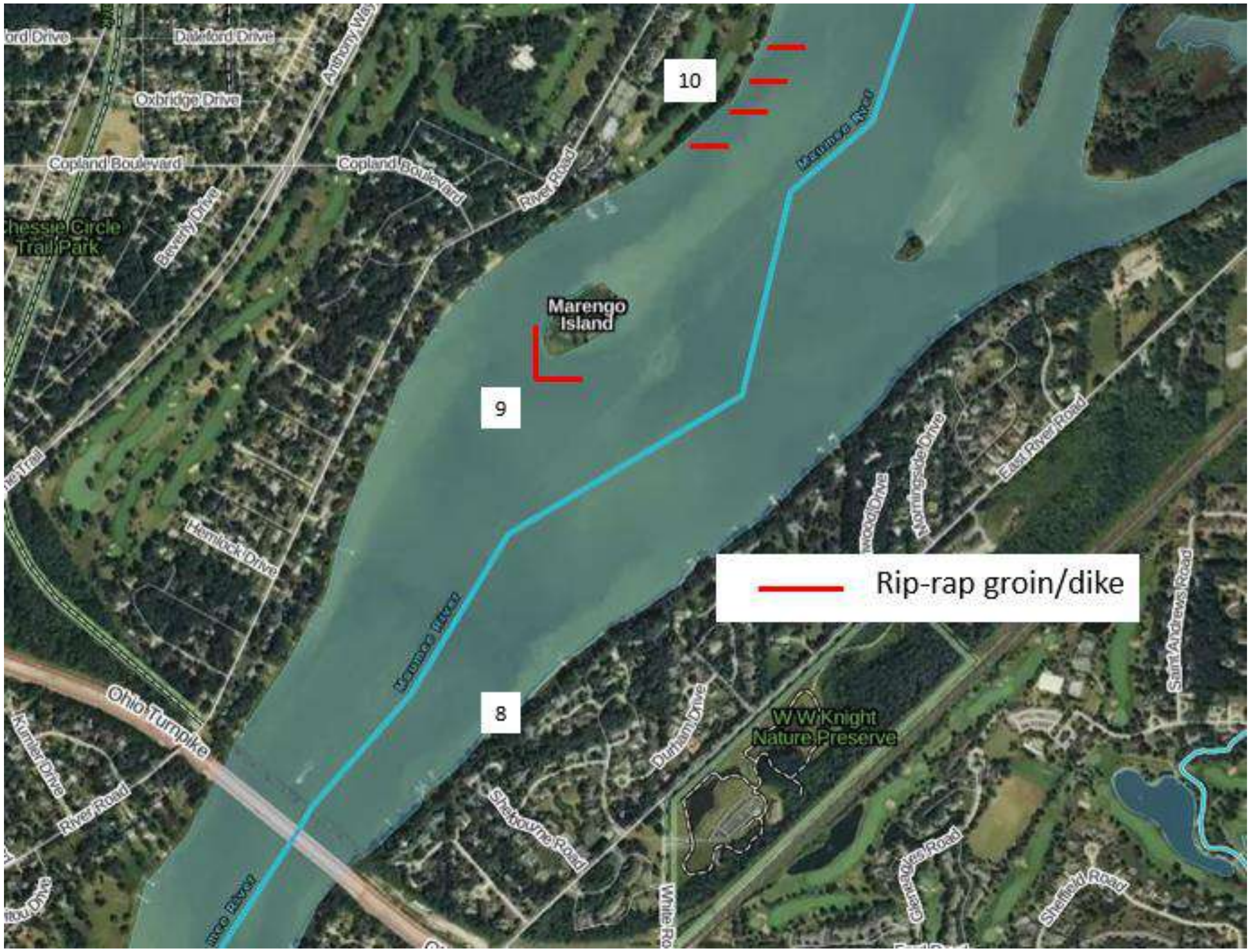


Figure 26. Segment 2 of study reach with project sites labeled.

Table 3. Segment 3 (Grassy Island to Delaware/Horseshoe Island Complex) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
11	- high Unionid mussels abundance (individuals >10mm) and richness	*Protection* - Avoid changes to flow or structures near upstream end of island	- mussel bed preservation	none	high	none	high	**3**
12	- low total fish abundance and richness across August sampling methods - low total fish abundance for July electrofishing - low July and August IBI - low percent EPT abundance and moderately low invertebrate taxa richness on Hester-Dendies	Install rip-rap wing-dikes along exposed shoreline	- Fish/invertebrate habitat augmentation	moderate	moderate	high	moderate	**14**

13	- historical island completely removed – could potentially re-establish	Install chevron-style rip-rap dike upstream of historical island site	- sediment accretion/island growth	high	low	high	low	**20**
14	- shallow cove environment and protection from harsh flows could help generate SAV - low August and moderately low July IBI - low percent EPT abundance and invertebrate taxa richness on Hester-Dendies	- Install rip-rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	moderate	low	**17**
15	- shallow cove environment and protection from harsh flows could help generate SAV - low total fish abundance and richness across August sampling methods in the side	- Install rip rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	low	moderate	**11**

	channel this cove faces (Grassy Island side channel)							
16	- highest Unionid mussel abundance and richness across sites	*Protection* - Avoid changes to flow or structures near upstream end of island	- mussel bed preservation	none	high	none	high	**2**
17	- shallow cove environment and protection from harsh flows could help generate SAV - low percent EPT abundance on Hester-Dendies	- Install rip rap wall to partially close cove or woody palisades along cove border - Dredge cove to 1.5 m	- SAV production - Phragmites prevention - promotion of native emergent vegetation	high	moderate	moderate	moderate	**15**

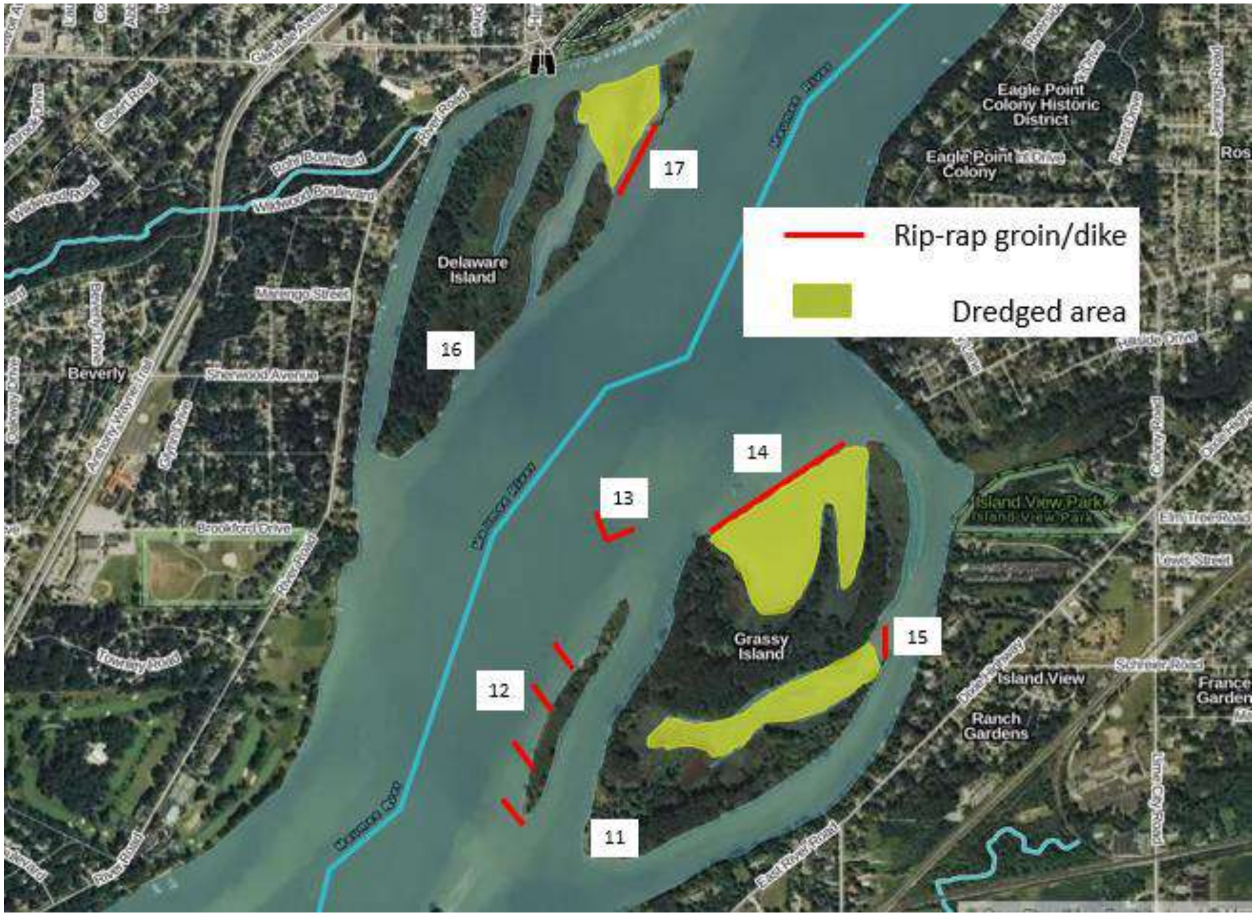


Figure 27. Segment 3 of study reach with project sites labeled.

Table 4. Segment 4: (Clark Island to Rt. 75 bridge) recommended project site summary table.

Project Site	**Site selection justifications**	**Recommendations**	**Goals**	**Anticipated effort**	**Success confidence**	**Unintended impact likelihood**	**Need**	**Priority rank**
18	- high Unionid mussel abundance (individuals >10mm)	*Protection* - Avoid changes to flow or structures around island	- mussel bed preservation	none	high	none	high	**4**
19	- island complex was historically larger - low total fish abundance and moderately low richness across August sampling methods - low total fish abundance for July electrofishing - low total invertebrate abundance and percent EPT taxa on Hester Dendies - moderately low Unionid mussel	Install chevron-style rip-rap dike at upstream end of island	- sediment accretion/island growth	high	low	moderate	moderate	**18**

	abundance and richness							
20	- not sampled, existing rip-rap can benefit fish and invertebrate communities	*Protection* - Keep rip rap structures previously installed to fix Rt. 75 bridge	- Fish/invertebrate habitat augmentation	none	moderate	none	high	**6**

Figure 28. Segment 4 of study reach with project sites labeled.

Recommended project prioritization summary

Highest Priority (Rankings 1-6; Project sites 1, 16, 11, 18, 6, 20)

The highest priority sites are those in which we are trying to protect already high-quality habitat. These sites require no action other than simply not disturbing them. These projects include sites that contain known spawning grounds for walleye (project site 1), potential important fish and invertebrate habitat (site 20), and areas of high Unionid mussel abundance and/or richness (sites 16, 11, 18, 6). Site 1 is ranked the highest of all these sites as it was deemed important from both previous knowledge and our catch data. In regards to the Unionid mussel protection sites, 16 had the greatest Unionid richness and abundance of all mussel sites across both mussel size classes, and thus is ranked highest among them, while with the other sites the richness and/or abundance of a particular size class was lower. Site 20 ended up being ranked the lowest out of these sites since we did not actually sample there, thus we can only say with some confidence that this is an already high quality fish/invertebrate site.

Moderate-High Priority (Rankings 7-10; Project sites 5, 4, 2, 8)

In general, the moderate-high priority sites are those which call for the installation of habitat augmenting features such as root wads or downed trees along the shoreline. These projects are low cost, and can be a quick and effective means of attracting fish and invertebrates to these sites and supporting these populations in the future. All of these sites demonstrated some lack of habitat heterogeneity, which was reflected in fish and/or mussel catch. Project site 5, which signifies the center of the western shoreline of Grape Island, lacked any semblance of significant riparian vegetation or woody debris besides some tall grasses, and also thanks to low August fish abundance and low July fish abundance and richness, was ranked the highest out of these sites. Site 4 also had low August fish abundance and low July fish abundance and richness and contained a bare shoreline, but did contain some downed woody debris, and thus is ranked just below project 5. Site 2 also had these same issues, with the addition of low Unionid mussel richness and abundance, but did already have some pre-existing riparian vegetation and downed tree branches overhanging the shoreline, and is thus ranked just below site 4. Site 8 did contain rip-rap habitat which is an improvement over the mostly bare shorelines of project sites 5, 4, and 2, and thus is ranked lower. Despite this rip-rap however, the site still had issues with fish species richness during August sampling and both richness and abundance during July, which may be a result of the exposed nature of this shoreline to high flows. The addition of woody debris at this site could create some disturbance to these high flows and will add additional habitat heterogeneity to attract more species of fish.

Moderate-Low Priority (Rankings 11-16; Project sites 15, 3, 7, 12, 17)

The moderate-low priority sites are those which call for habitat augmentation through the use of dredging activities and flow barriers outside of coves to generate SAV beds and/or river training structures such as wing dikes that will require moderate to high costs, may have a moderate to high degree of unintended impacts on flow, and may have a few issues regarding success confidence. For example, the projects related to SAV production may face considerable challenges. This is mostly due to the high turbidity of the Maumee River which has contributed to the prevention of SAV growth in the first place, along with invasive plant growth such as

Phragmites. Dredging these coves to 1.5 m may help with both these problems because it is at the threshold depth of where Phragmites and other emergent plants in general begin to be discouraged from growing (Sohngen et al. 2008) and it may be shallow enough to negate the effect of the turbid water on blocking sunlight and thus inhibiting submerged plant growth. However, it is unknown whether the turbid waters will still impact SAV growth at that depth, so success confidence for these projects is only ranked as moderate.

Site 15 is ranked the highest of the moderate-low priority projects as it calls for the dredging of a cove whose mouth faces downstream into the Grassy side channel, so overall effects of flow are likely to be minimal. Also, although the cove itself was not sampled, August fish richness, abundance and IBI scores in the side channel it faces were low, so work in this cove could improve the fish populations in this area. Site 3 calls for a similar project, and is also unlikely to majorly affect flows or downstream communities as the mouth of the cove faces downstream. Combined August fish catch data indicates richness and abundance were slightly better near this site than near site 15, thus it is ranked lower on the priority list. Site 7, which calls for installation of wing dikes, may have more of an impact on flow, but the negative consequences of this is ranked only as moderate as no high-quality sites were identified immediately downstream of this site. Site 12, on the other hand, which also calls for wing dikes, presents the same flow issues, but potentially with greater consequences as a the site which contained our best Unionid catch (site 16) is just downstream of site 12, and thus is ranked lower. Site 17 calls for another SAV augmentation project, and although this cove was not sampled for fish directly, sampling around the unnamed island directly downstream of it demonstrated moderate fish abundance and richness according to combined August catch data, thus its priority was ranked below 12.

Lowest Priority (Rankings 17-20; Project sites 9, 14, 19, 10, 13)

Like the moderate-low priority projects, these also include a combination of SAV habitat augmentation and river training structure installation projects, but with potentially higher costs and/or lower reward. For example, several of these projects call for the installation of chevron dikes to either influence growth of existing small islands or to aid in the growth of new ones, but these projects may be some of the most costly. To be successful, these projects may require the movement of previously dredged material downstream of the dike to aid in success of island creation. Additionally, these projects would generally take place mid-channel in deeper waters than the wing-dike projects, and this would require more material to construct the dikes. Although the chevron dike projects could have the potential to be some of the most important given the benefits these island complexes can bring to the region and the area’s history of island loss, it will take time for the new island land to fully develop and generate preferred habitat for fish and invertebrates. Consequently, it may be several years before measureable ecological improvements are seen from the chevron dike projects.

Of these lowest priority projects, project site 9 scored the best. Although the cost of the project is likely to be high, and the chevron dike flow diversion may potentially affect high quality habitat downstream (e.g. site 11), the ecological need for the project is high since this site demonstrated both low richness and abundance for fish and mussels across sampling dates and methods. Project site 14, which calls for SAV bed augmentation, although may cost slightly less and have lower flow impact than project 9, the fish richness and abundance across sampling methods in this cove did not indicate it was one of the more degraded sites, thus the need for the project is low. Project site 19 calls for another chevron dike to be installed and faces the same challenges as the chevron dike at site 9, but fish and mussel catch indicated this small island (Corbutt) was not as degraded as the small island near project site 9 (Marengo Island). Site 10 is another project recommended at a site that was not actually sampled, nor is it directly adjacent to a site that was sampled, so our confidence of success in this project is low. The wing dike flow diversion at this site could also potentially impact the upstream end of Delaware Island which had demonstrated high fish abundance and richness across sampling dates and methods. Project site 13 is ranked the lowest of all these projects. It received the lowest possible score in this ranking system, as the chevron dike project will likely have a high cost, high chances of impacting nearby fish and invertebrate communities by impacting flows, low need as the other islands provide other ample opportunities for habitat restoration, and low confidence in success as the development of this island and thus the ecological improvements could take several years to be detected.

Benefits and next steps

If successfully implemented, these restoration projects could greatly benefit the fish and invertebrate communities in the Maumee River. Evaluating the financial and legal components of these projects will be an important next step in implementing these projects. Specifically, coordinating with engineers will allow us to estimate the project costs as well as potential impacts on fluvial processes in the river, and communicating with the various stakeholders who either own the land at each project site or make other use of it is vital to then making a final determination as to where projects can be carried out. Once this phase is complete and one or more projects are implemented, extensive monitoring must occur in order to ensure the fish and invertebrate communities are responding positively to restoration efforts. This project has established the spatial distribution of high-quality and degraded fish and invertebrate habitat in a biologically important stretch of the Maumee River, and has established a baseline of conditions by which further sampling and community evaluation should be compared to.

Although we cannot make exact predictions as to how Ohio EPA biotic community and habitat metrics (IBI, ICI, MIwb, QHEI) will be affected by these restoration projects, we are confident that many of these restoration projects will help these sites approach or meet Ohio EPA restoration targets for Warmwater Habitat (WWH) in order to remove BUIs affecting the region. In addition to removing three BUIs (3.) Degradation of fish and wildlife populations 6.) Degradation of benthos and 14.) Loss of fish and wildlife habitat), these projects could bring a variety of ecological improvements that are unique to this river. For example, in 2018, the Toledo Zoo began raising and stocking juvenile Lake Sturgeon (*Acipenser fulvescens*) into the Maumee River at Walbridge Park just downstream of the Delaware/Horseshoe island complex. Given the potential habitat improvements created by these projects, the suggested restoration activities may improve Sturgeon retention in the years to come. Additionally, given that 17 fish species which once historically spawned in great numbers in the Maumee River no longer do (Karr et al. 1985), we would expect to see a resurgence in the spawning activities of these fishes, particularly those which have yet to be extirpated from the region. For example, Northern pike, which are still present in the river but whose spawning activities were reduced in the river due to a loss of aquatic vegetation, may benefit directly from restoration projects which directly address the lack of submerged aquatic vegetation in the river. Overall, this Maumee fish and invertebrate assessment, the restoration efforts which will emerge from it, and the subsequent monitoring and evaluation of their benefits will play a fundamental role in eliminating the AOC status of the Maumee.

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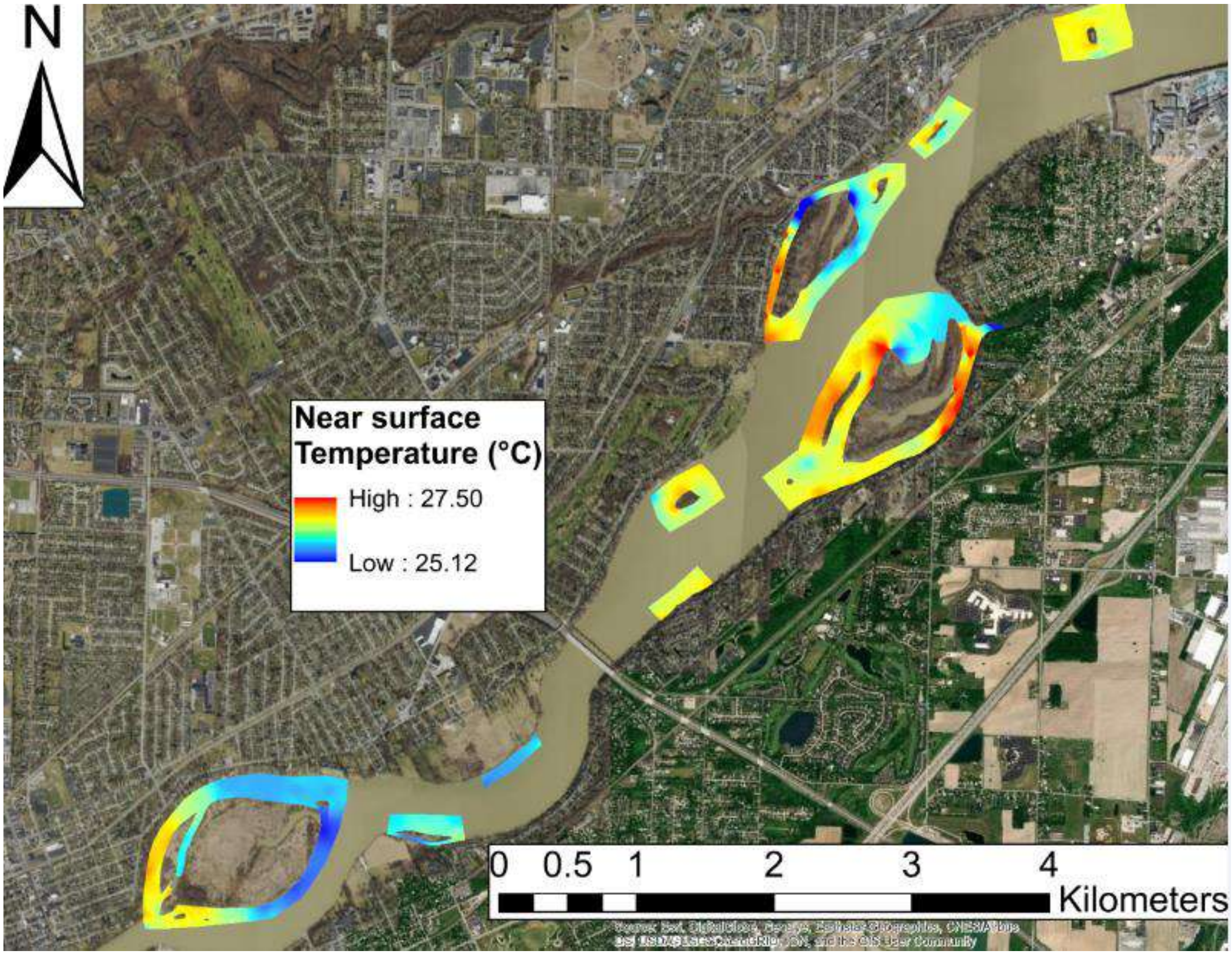
Appendix A: Abiotic and bathymetry data

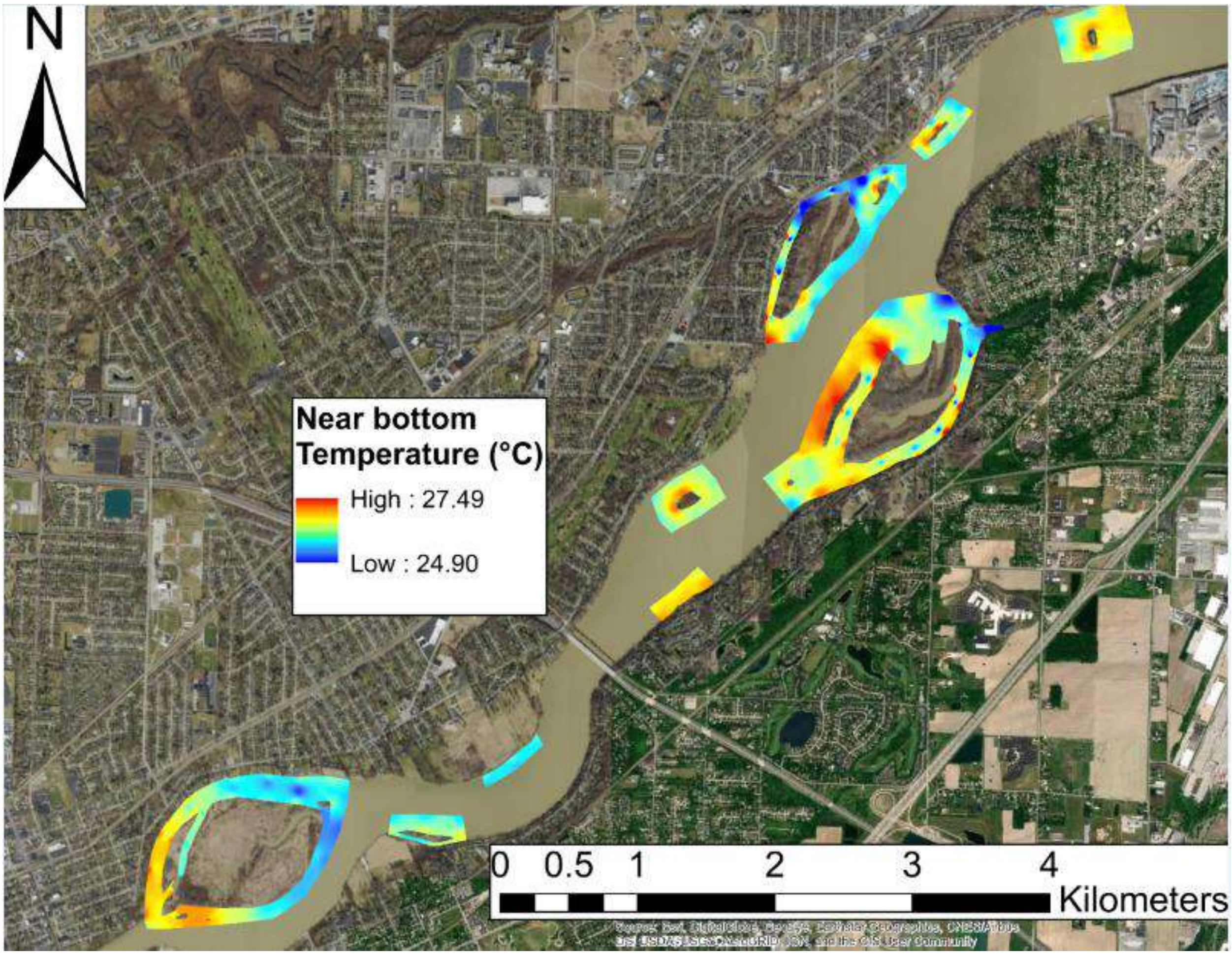
Table A.1: Average abiotic data at each fish sampling site (see study site map in "Field Sampling Methods"). Values are averages across electrofishing and fish trawl transects from August 2019.

Sampling site number	Temperature (°C)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	Conductivity (µS/cm)	pH	Depth (m)
1	26.59	6.47	14.03	414.72	8.53	1.43
2	26.47	8.70	14.90	428.04	8.62	2.08
3	25.92	7.34	19.42	450.73	8.52	2.11
4	25.97	6.36	21.33	438.13	8.44	1.84
5	25.94	6.81	24.29	436.24	8.51	1.20
6	26.09	7.52	18.80	428.44	8.65	1.80
7	25.98	5.15	27.16	421.67	8.25	1.87
8	26.59	4.83	23.67	405.13	8.10	2.18
9	26.40	4.40	29.33	403.02	7.86	2.09
10	26.59	6.54	37.96	408.20	8.23	1.10
11	26.71	6.80	39.86	402.79	8.26	1.50
12	26.63	7.58	37.07	406.84	8.36	1.20
13	26.16	6.03	57.42	406.54	8.05	0.53
14	25.77	5.74	20.97	448.19	7.96	0.84
15	26.09	6.40	45.79	410.02	8.13	1.27
16	26.68	4.43	47.44	409.39	7.86	1.38
17	26.11	3.63	55.47	412.54	7.67	2.43
18	26.15	4.60	54.93	423.94	7.84	1.02
19	26.43	4.94	57.60	419.74	7.87	0.65
20	26.35	4.39	53.96	417.96	7.84	2.02
21	26.52	4.53	58.36	422.37	7.84	1.39



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A.1. Near surface (~0.5-1.0m below surface) temperature map interpolated from data collected in August 2019.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A.2. Near bottom (~0.5-1.0m from bottom) temperature map interpolated from data collected in August 2019.

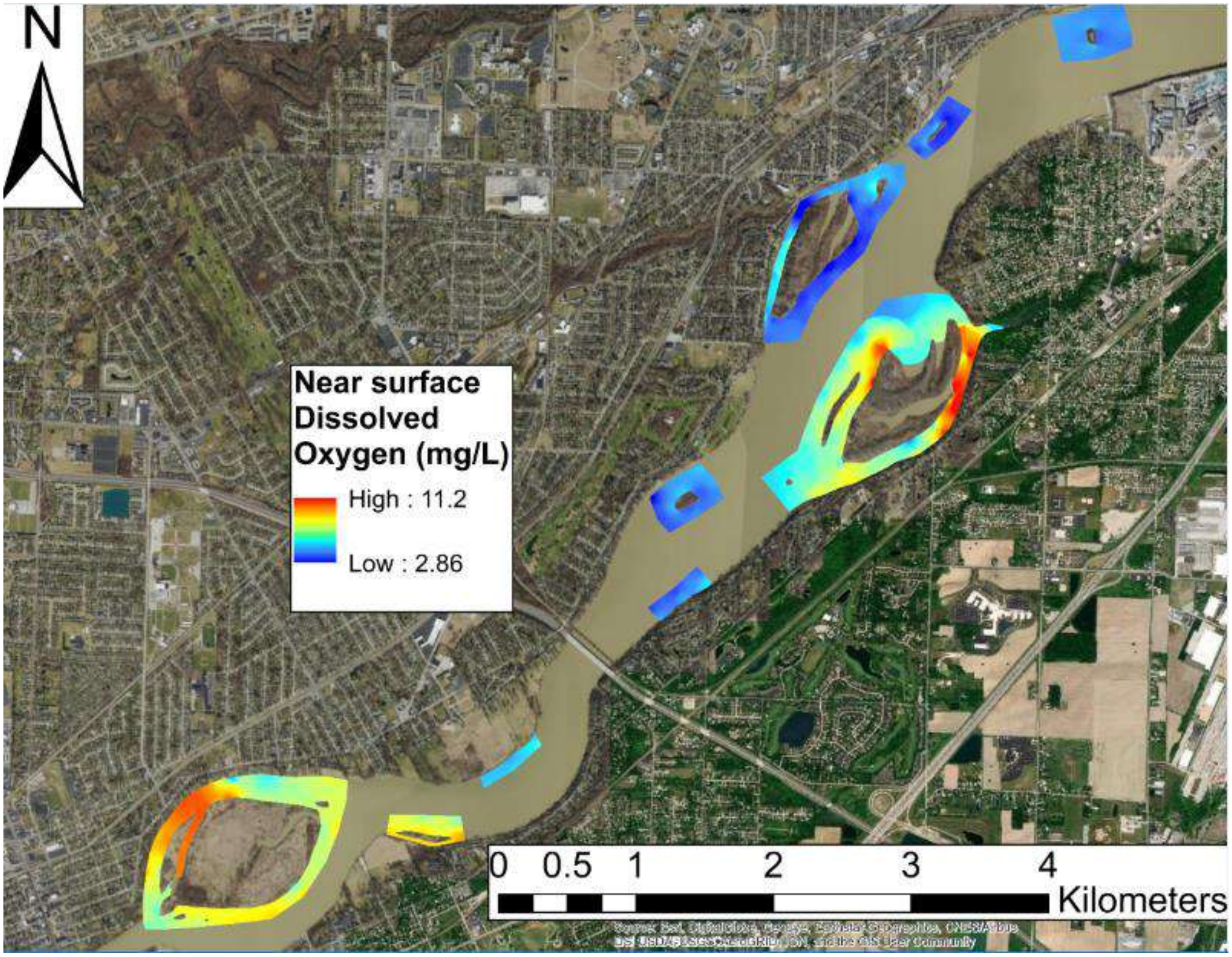


Figure A.3. Near surface (~0.5-1.0m below surface) dissolved oxygen map interpolated from data collected in August 2019.

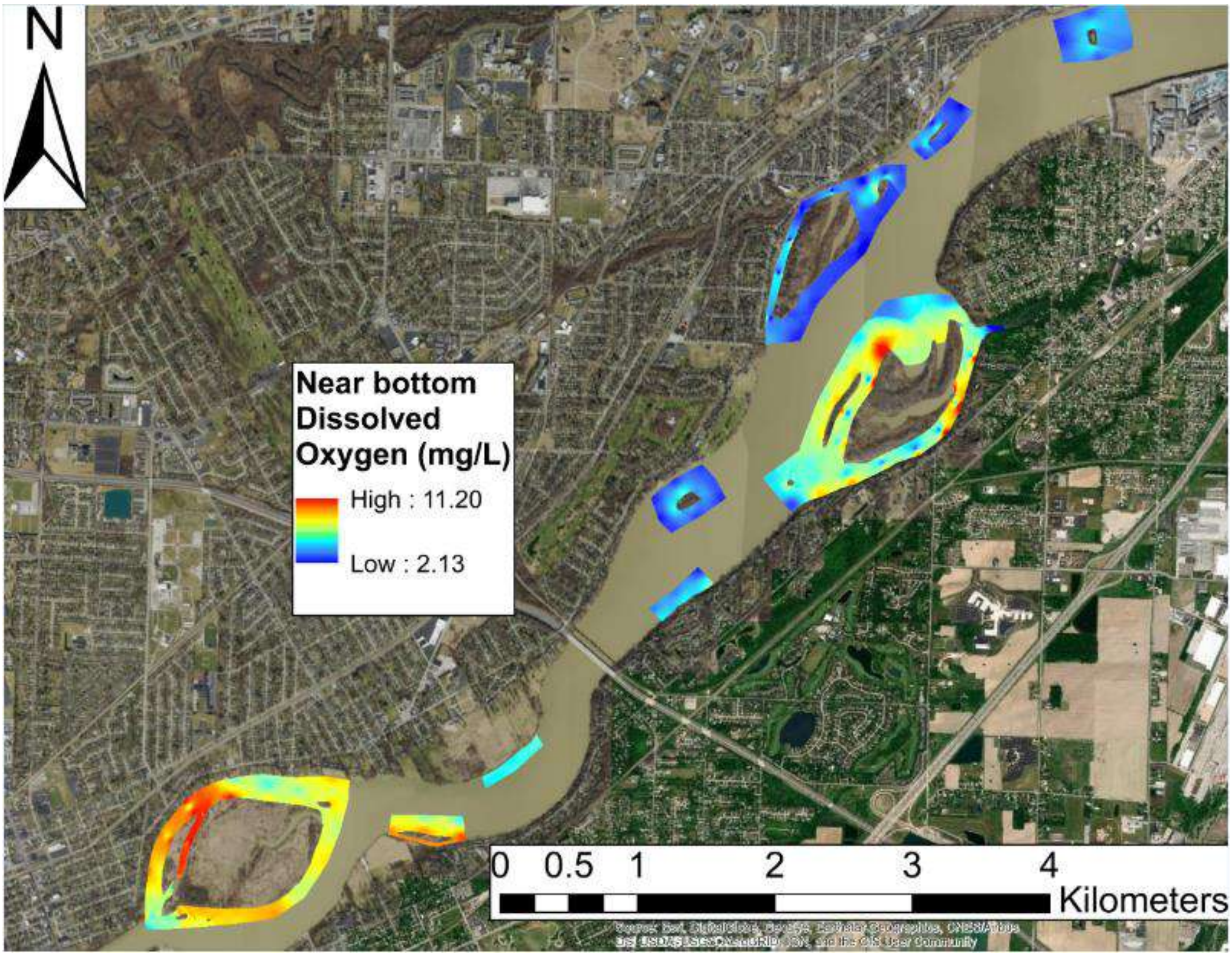
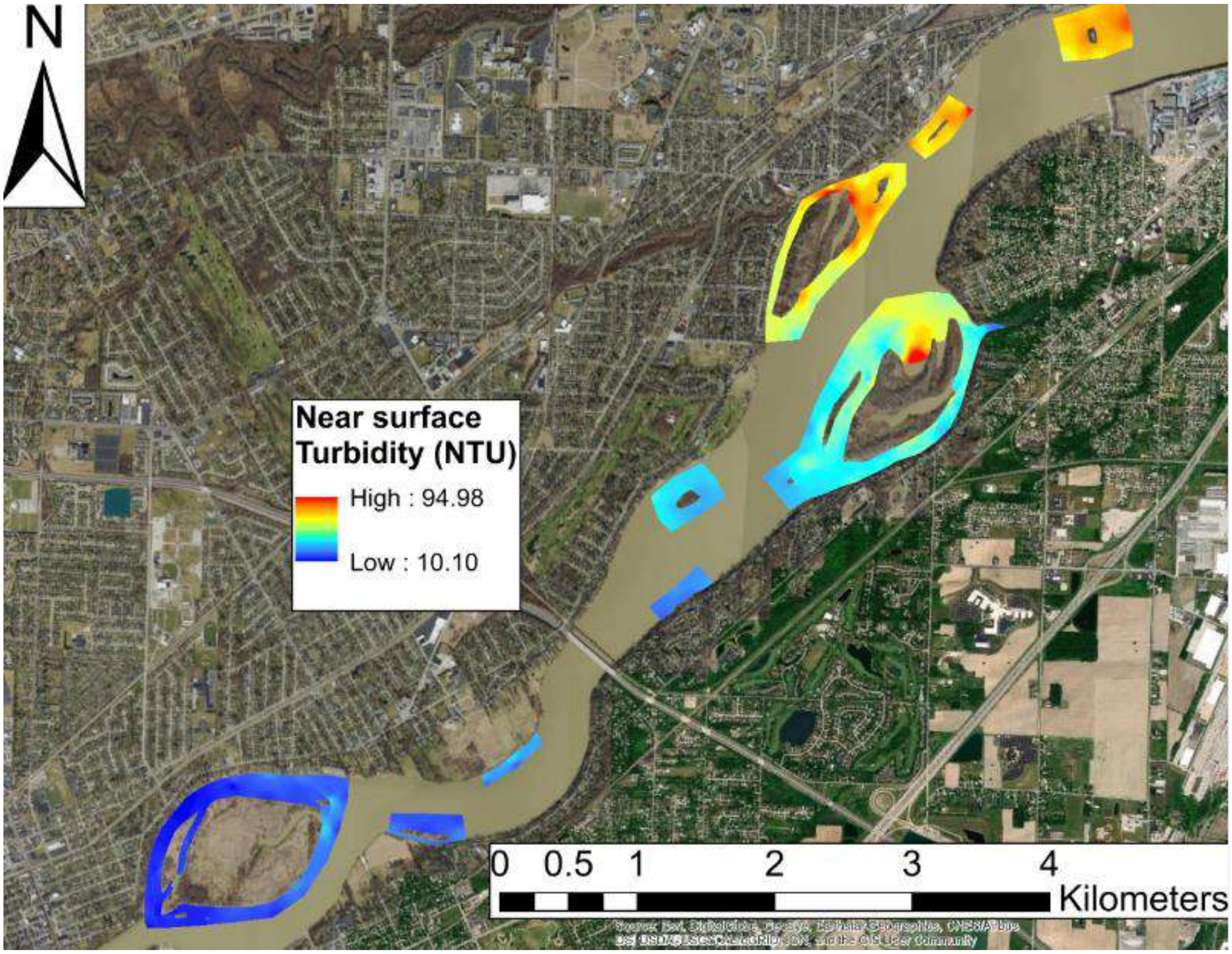


Figure A.4. Near bottom (~0.5-1.0m from bottom) dissolved oxygen map interpolated from data collected in August 2019.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A.5. Near surface (~0.5-1.0m below surface) turbidity map interpolated from data collected in August 2019.

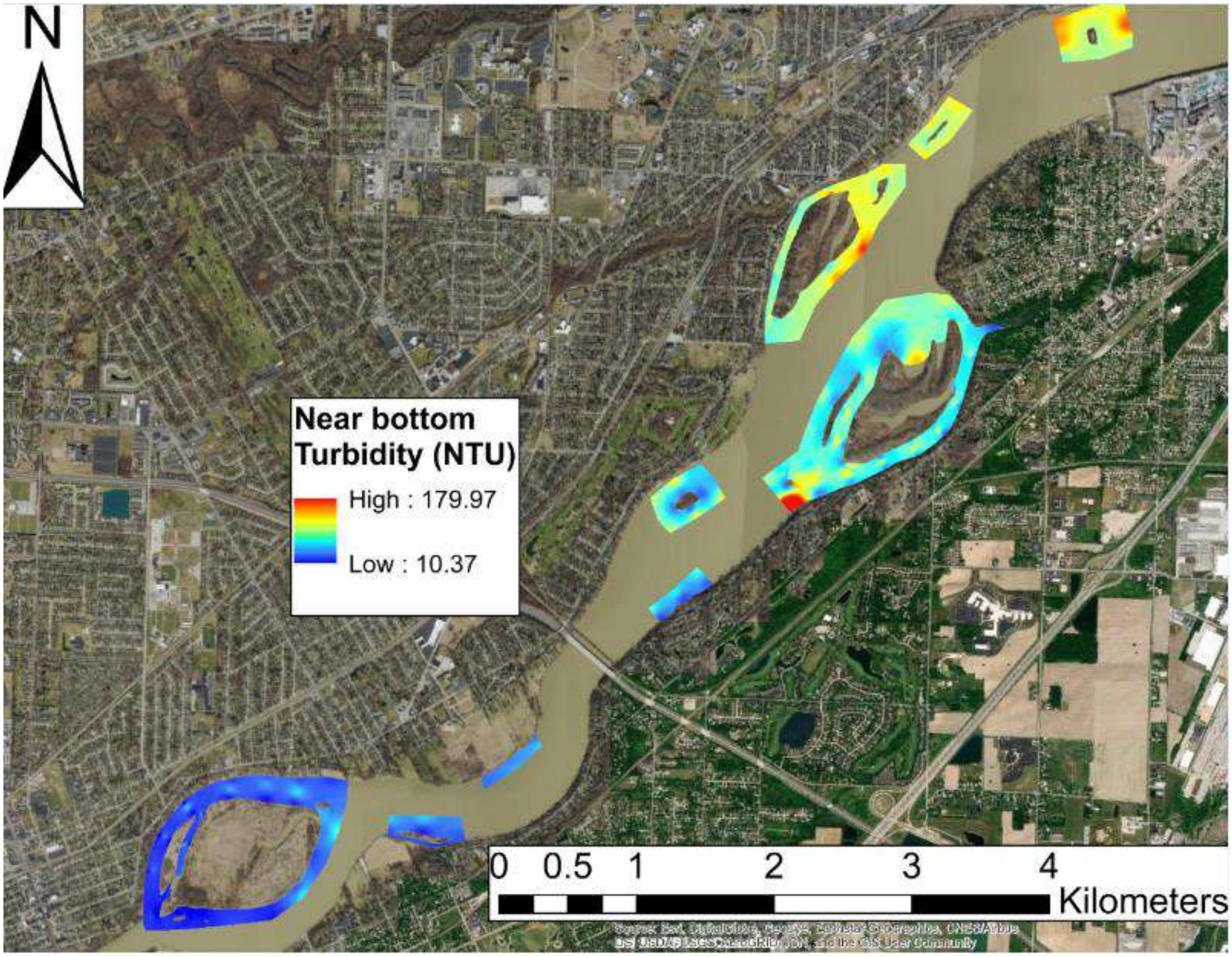


Figure A.6. Near bottom (~0.5-1.0m from bottom) turbidity map interpolated from data collected in August 2019.

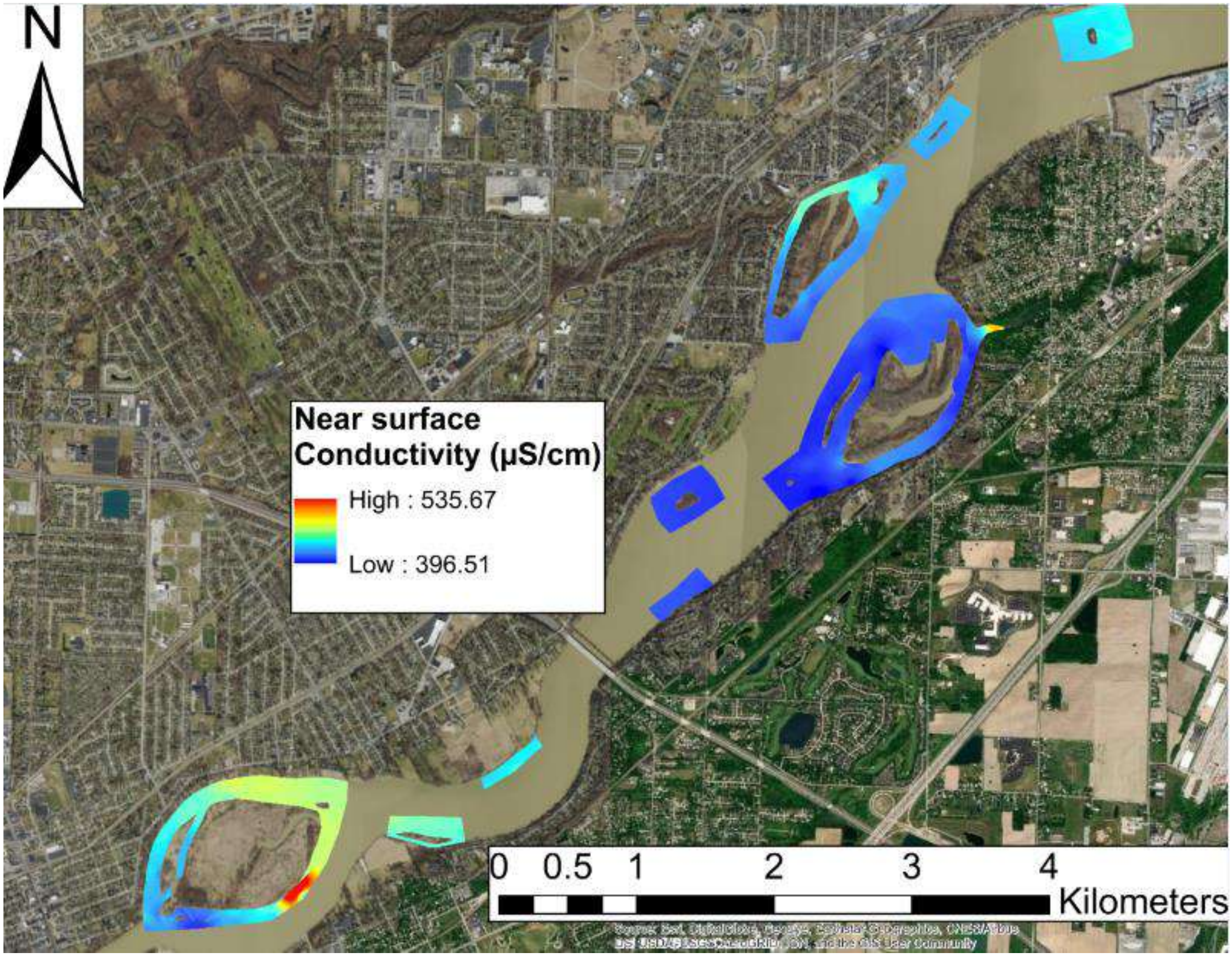


Figure A.7. Near surface (~0.5-1.0m below surface) conductivity map interpolated from data collected in August 2019.

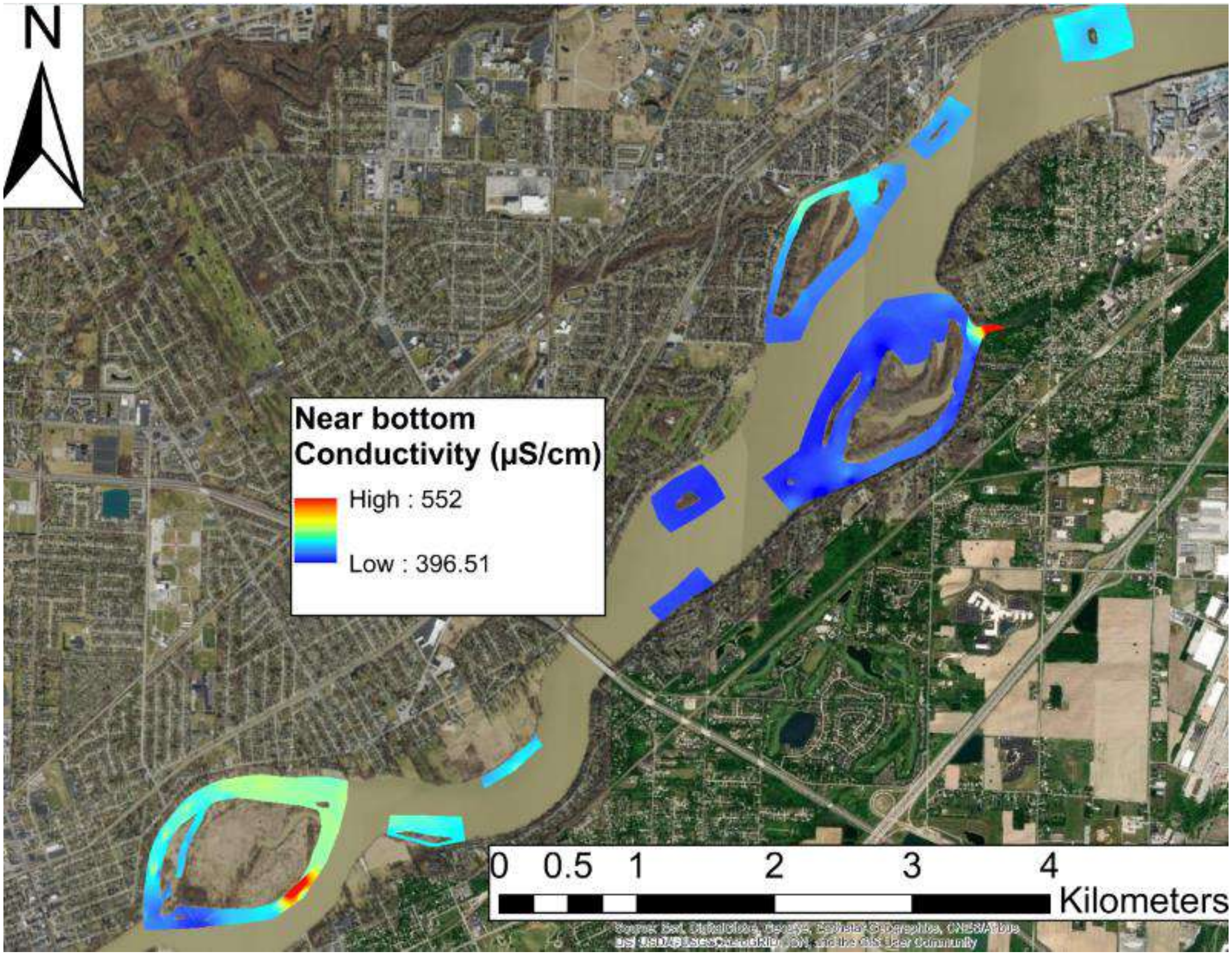


Figure A.8. Near bottom (~0.5-1.0m from bottom) conductivity map interpolated from data collected in August 2019.

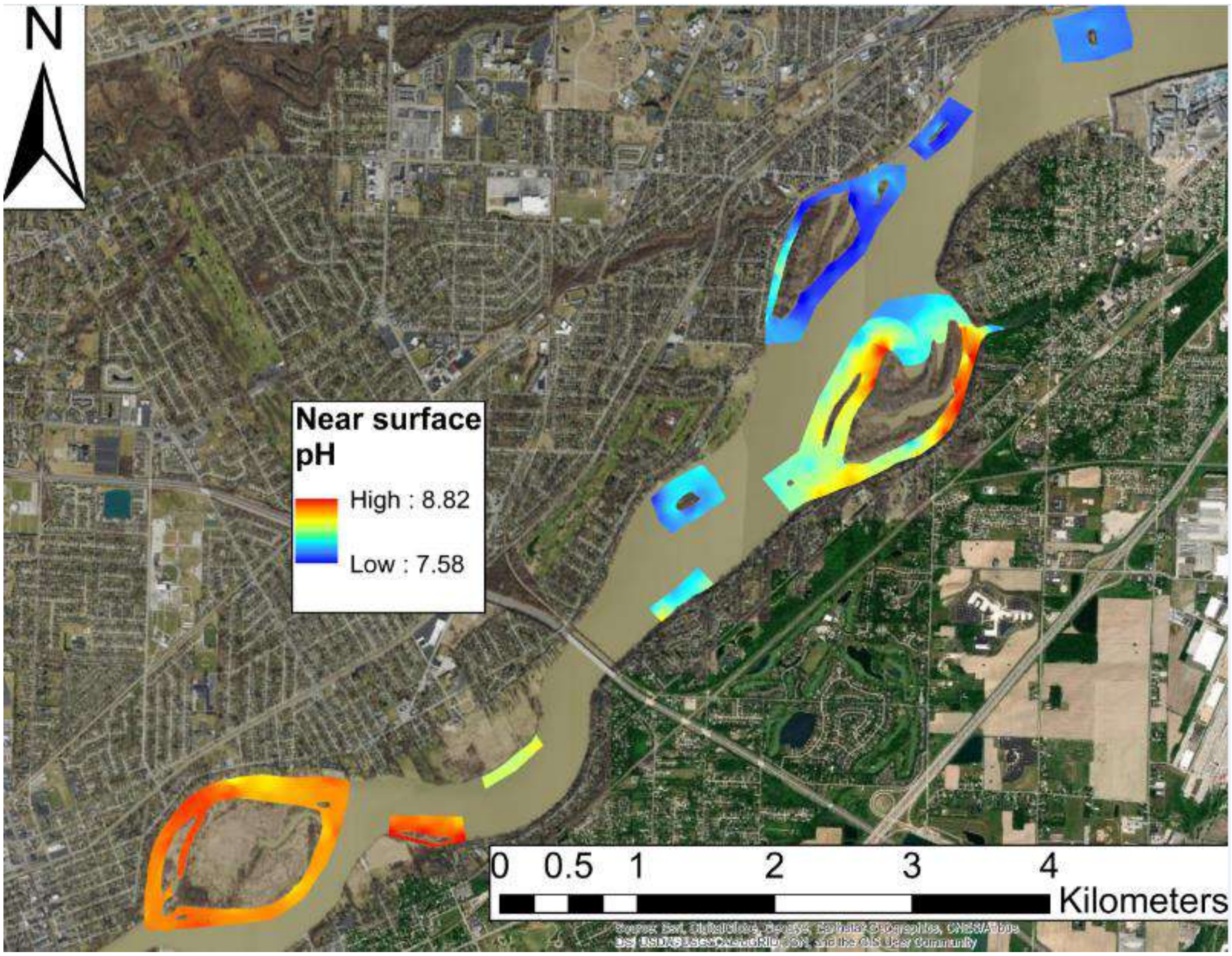


Figure A.9. Near surface (~0.5-1.0m below surface) pH map interpolated from data collected in August 2019.

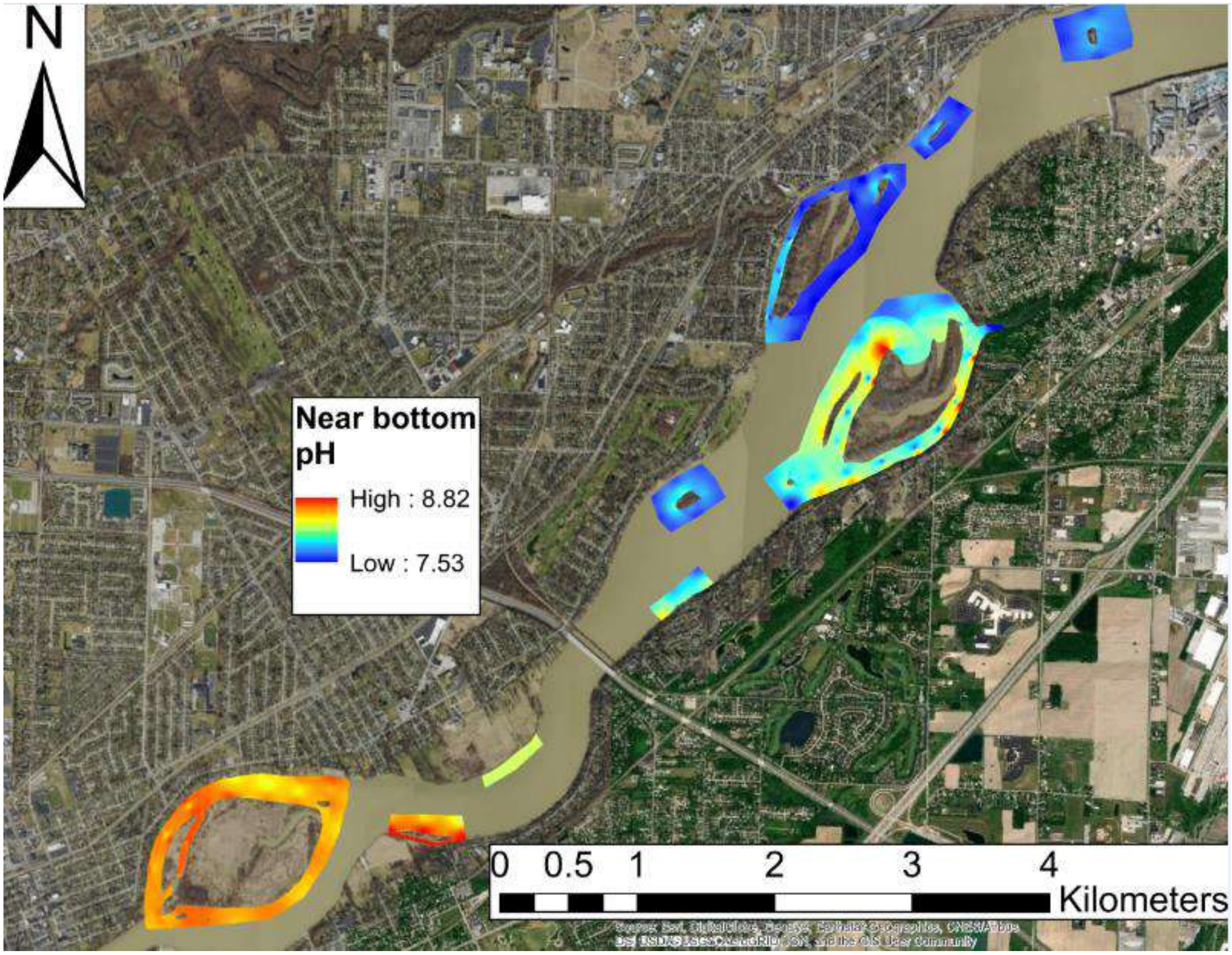


Figure A.10. Near bottom (~0.5-1.0m from bottom) pH map interpolated from data collected in August 2019.

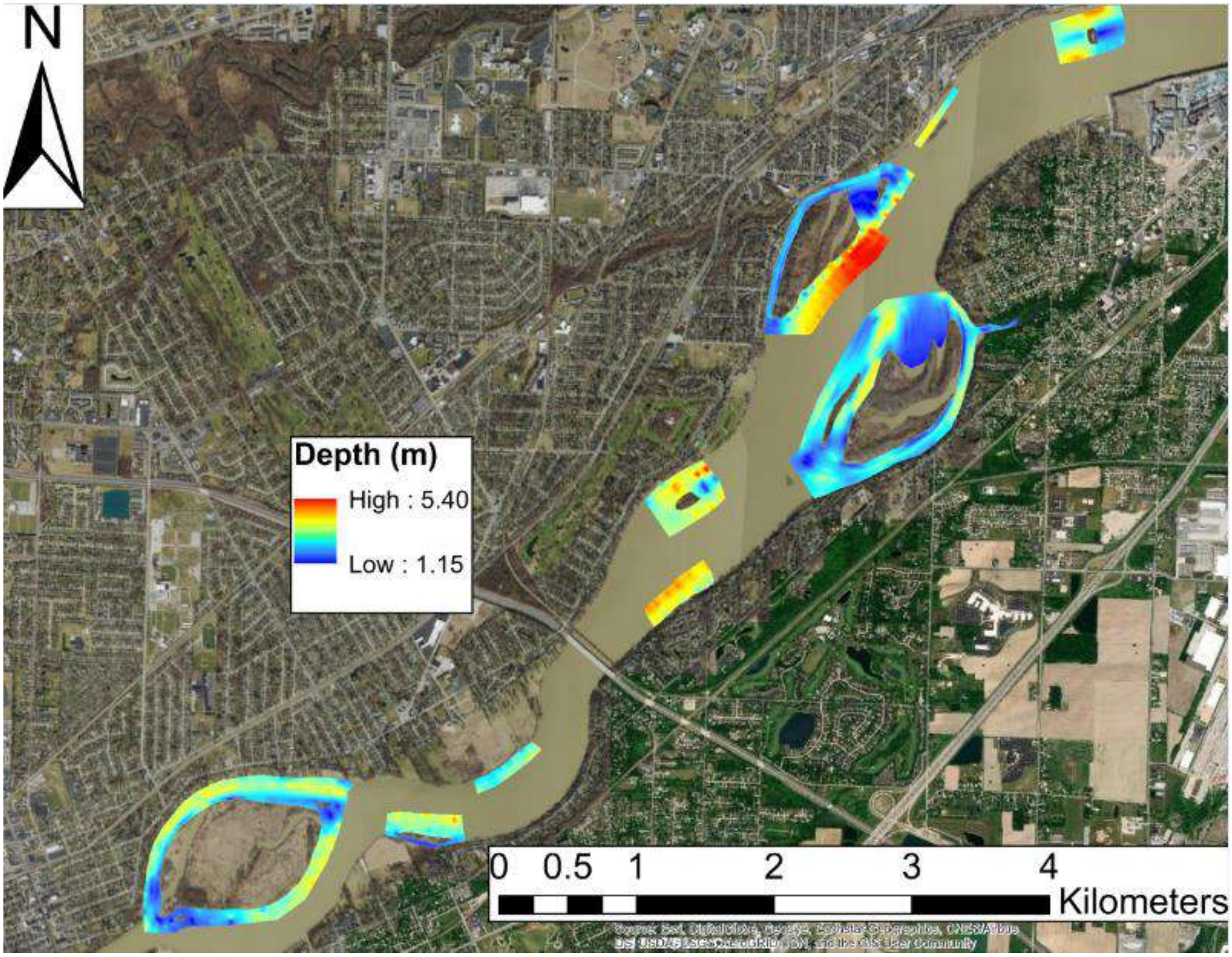


Figure A.11. Depth data interpolated from hydroacoustic tracks run in June 2019.

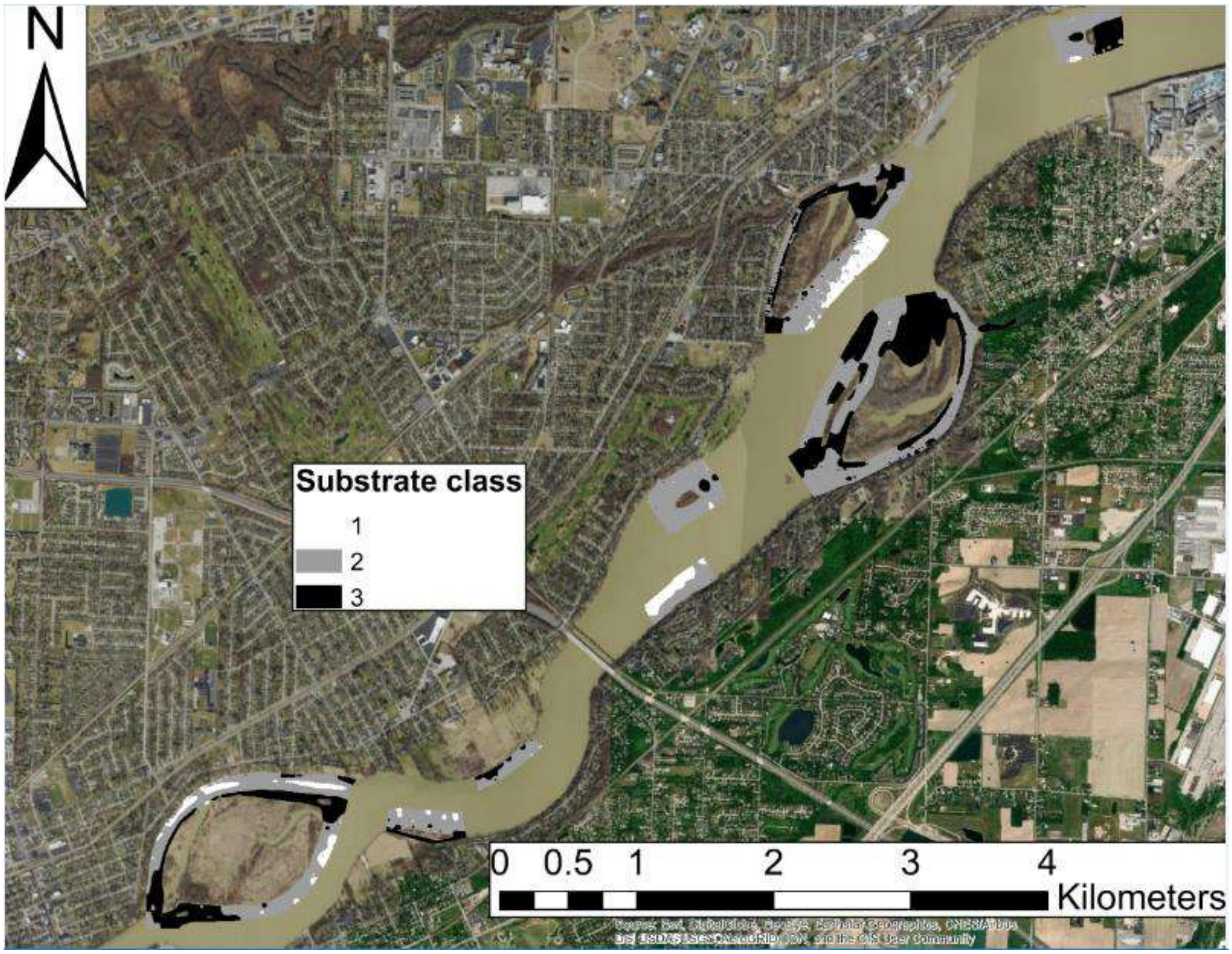


Figure A.12. Substrate classes interpolated from hydroacoustic tracks run in June 2019. Classes were distinguished using Biosonics Visual Habitat Software.

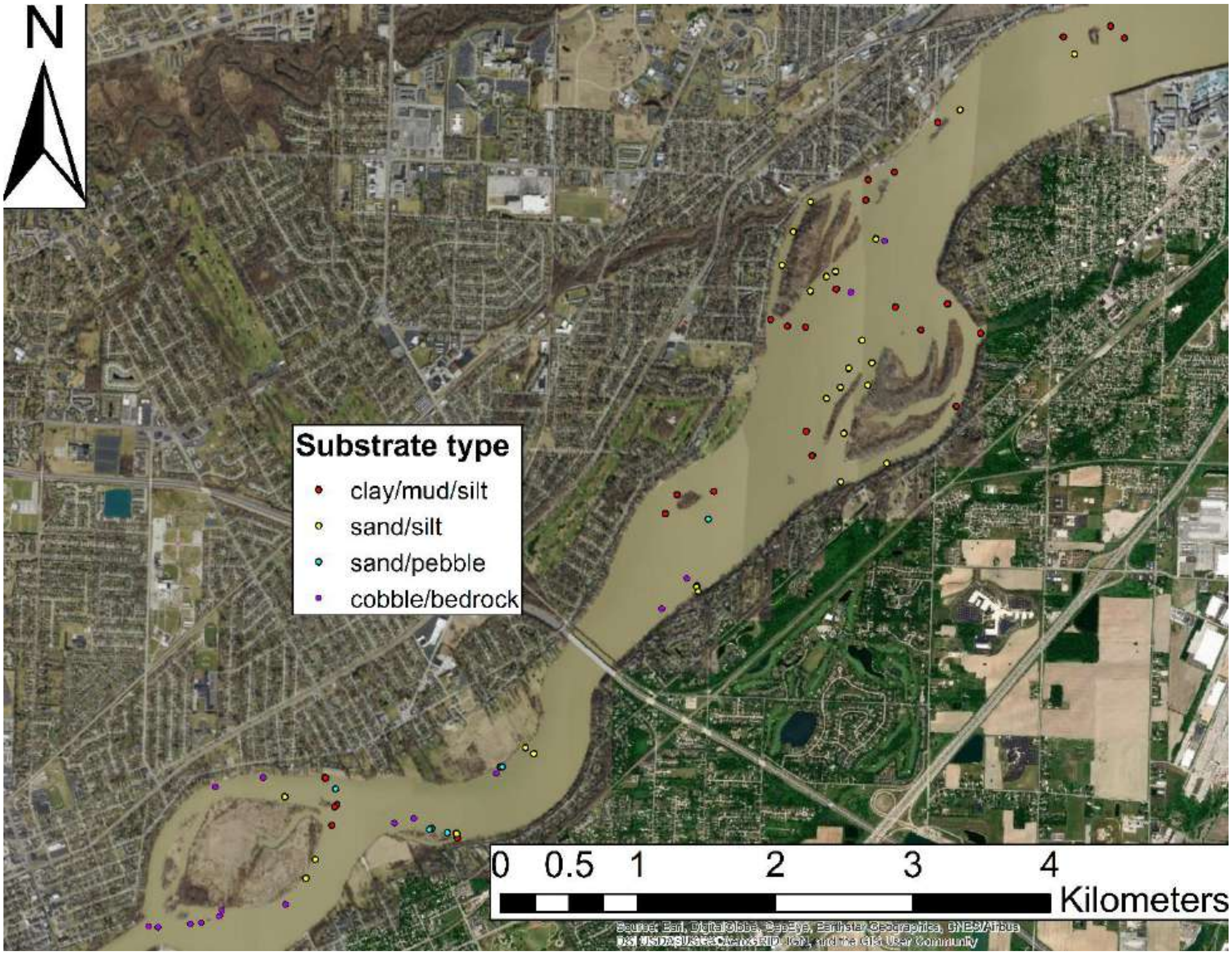


Figure A.13. Substrate types of sediments collected in Ponar grab samples for substrate ground-truthing in June 2019.

Appendix B: Additional analysis figures

Table B.1. Summary of AICc analysis of linear and logistic regression models used to explore relationships between catch data and various abiotic features for the august fish trawl, electrofishing and mussel trawl datasets.

Dataset	**Response variable**	**Predictor variables included in best model**	**Best model AICc weight**
Fish trawl	Species Richness	Temperature, depth, side of island	0.237
Fish trawl	Total Abundance	Temperature, substrate, side of island	0.076
Fish trawl	Presence of walleye	Intercept only	0.099
Fish trawl	Presence of centrarchids	Depth, conductivity	0.152
Electrofishing (August)	Species Richness	Temperature	0.087
Electrofishing (August)	IBI	Intercept only	0.113
Electrofishing (August)	Total Abundance	Dissolved oxygen, pH, conductivity	0.162
Electrofishing (August)	Presence of centrarchids	Conductivity, depth, side of island	0.186
Mussel trawl	Species Richness	Turbidity	0.055
Mussel trawl	Total Abundance	pH	0.091
Mussel trawl	Abundance of individuals >10mm	Dissolved oxygen	0.108

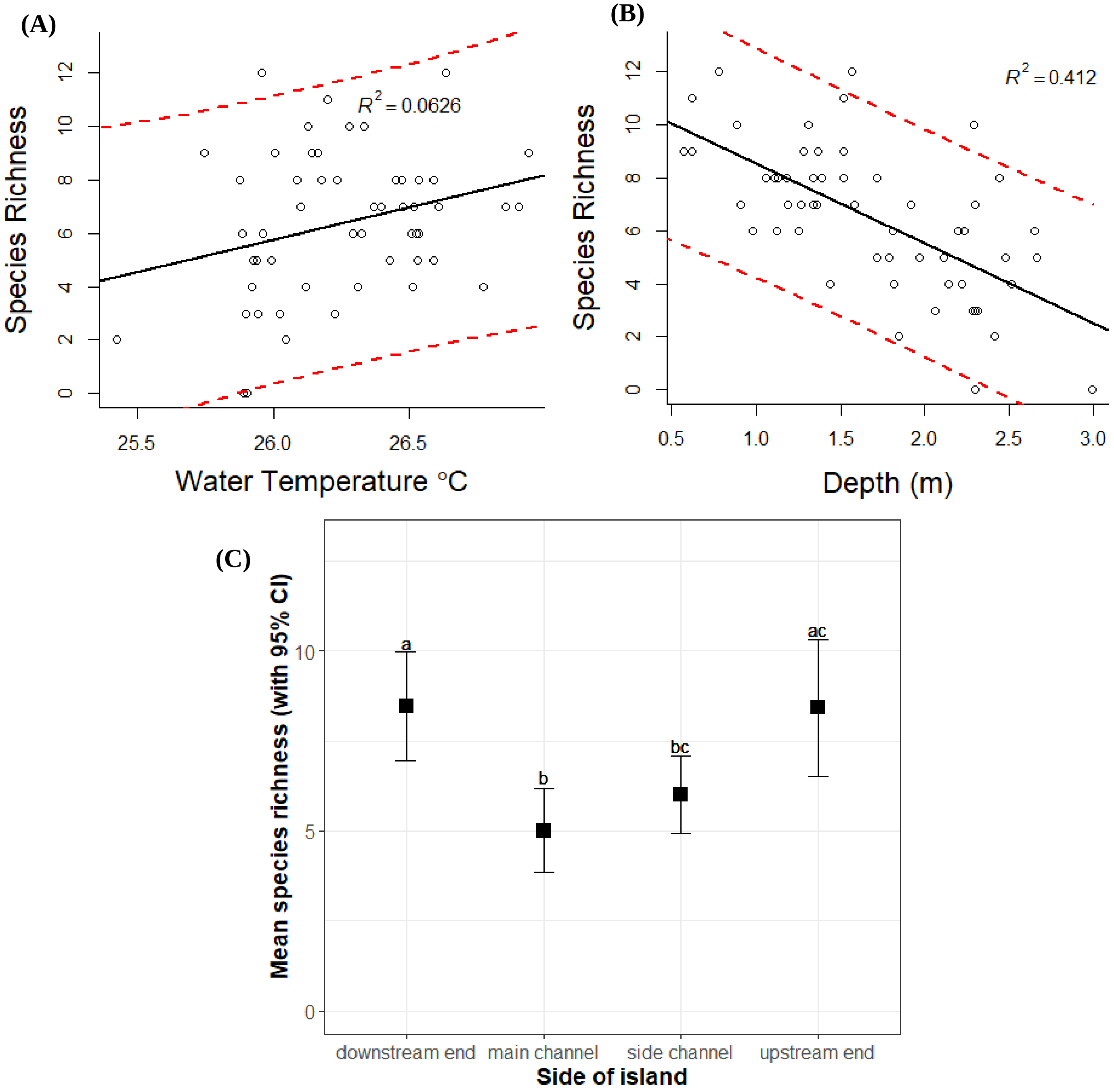


Figure B.1. Fish trawl species richness plotted against variables included in the best AICc model for the fish trawl dataset. For the continuous variables (**(A)** Water temperature; **(B)** Depth), solid black lines are fitted linear regressions and dashed red lines are 95% prediction bands. For the categorical variables (**(C)** Side of Island), error bars are 95% confidence intervals around the mean values. Different letters indicate statistically significant differences across groups.

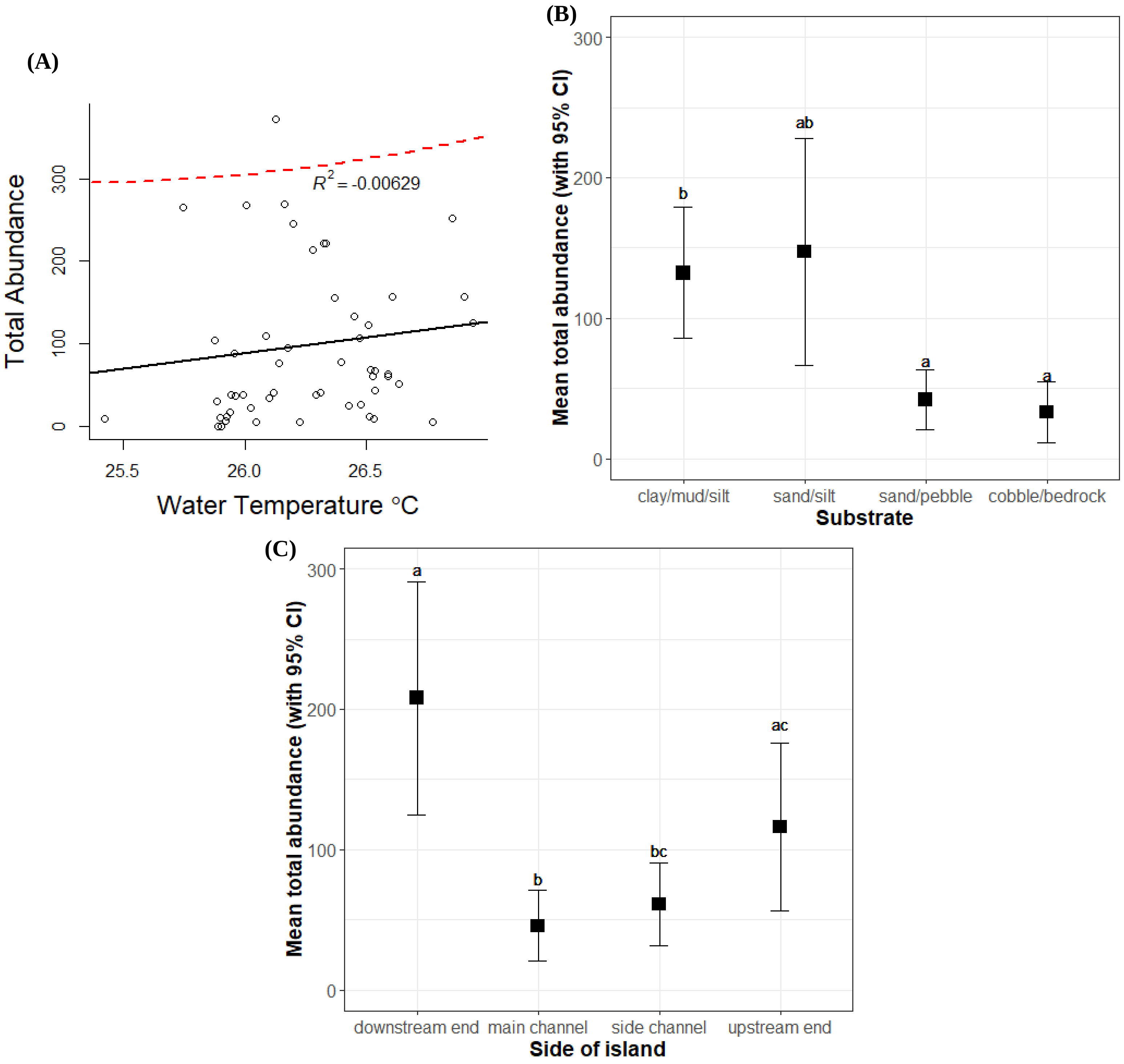


Figure B.2. Fish trawl total abundance plotted against variables included in the best AICc model for the fish trawl dataset. For the continuous variables (**(A)** Water temperature), solid black lines are fitted linear regressions and dashed red lines are 95% prediction bands. For the categorical variables (**(B)** Substrate; **(C)** Side of Island), error bars are 95% confidence intervals around the mean values. Different letters indicate statistically significant differences across groups.

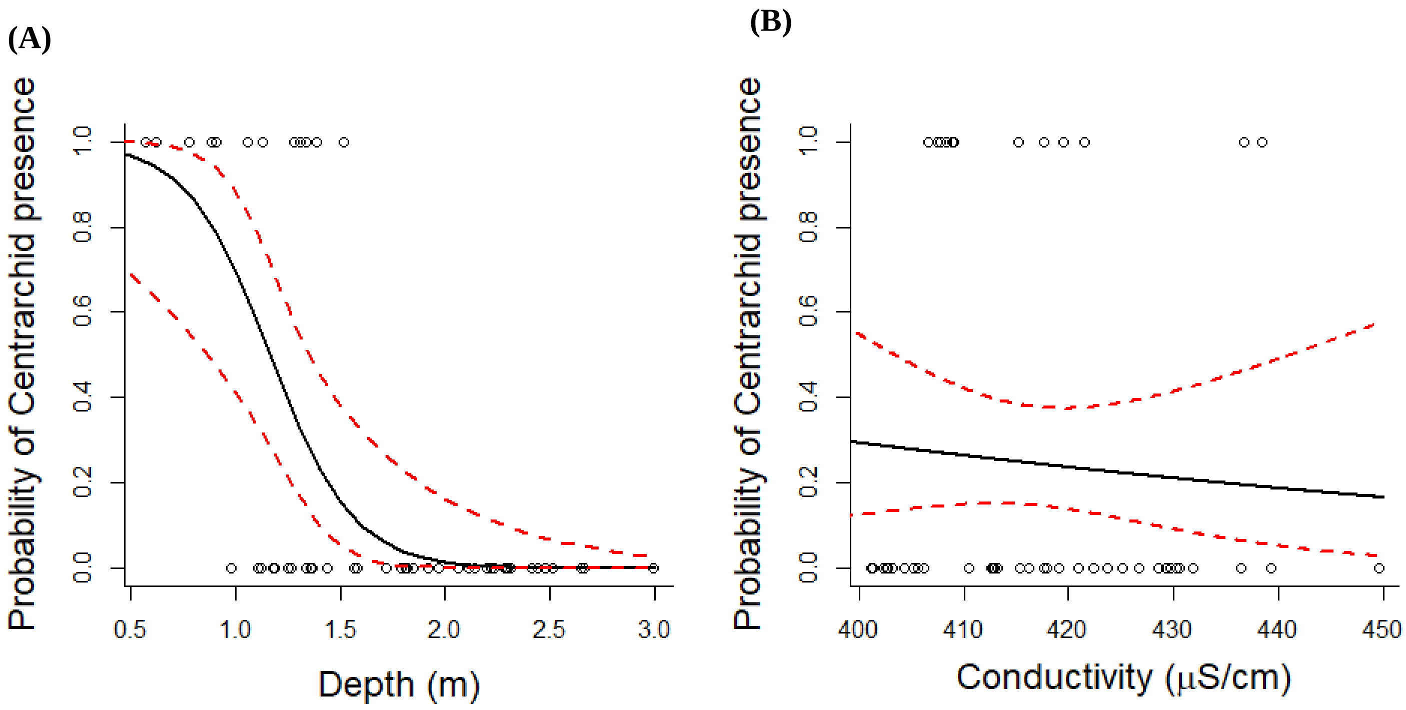


Figure B.3. Probability of centrarchids presence plotted against variables included in the best AICc model for the fish trawl dataset (**(A)** Depth; **(B)** Conductivity), solid black lines are fitted logistic regression curves and dashed red lines are 95% confidence bands.

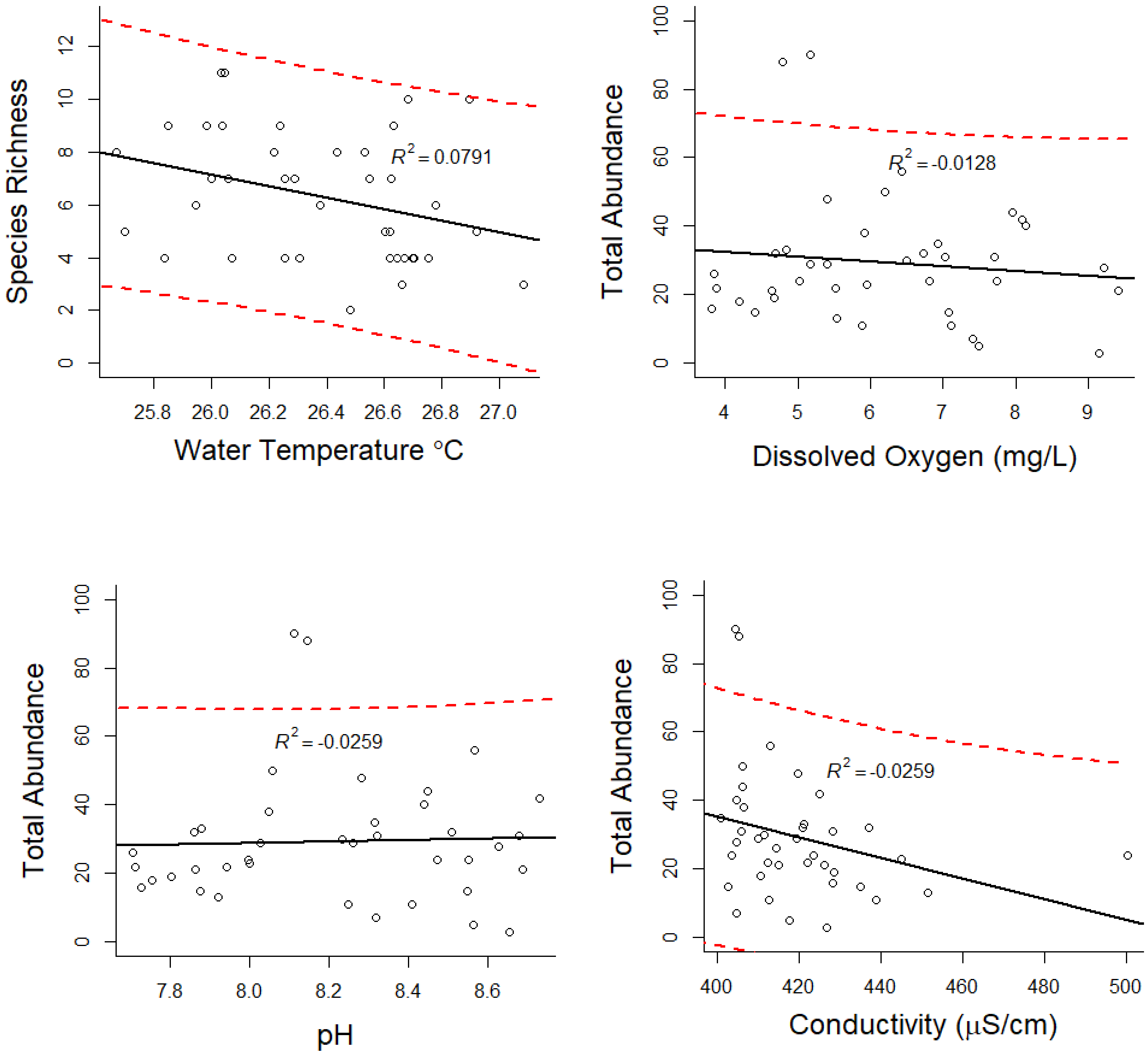


Figure B.4. Species Richness and Total Abundance plotted against variables included in the best AICc models for the electrofishing dataset (**(A)** Water temperature; **(B)** Dissolved Oxygen; **(C)** pH; **(D)** Conductivity)), solid black lines are fitted logistic regression curves and dashed red lines are 95% confidence bands.

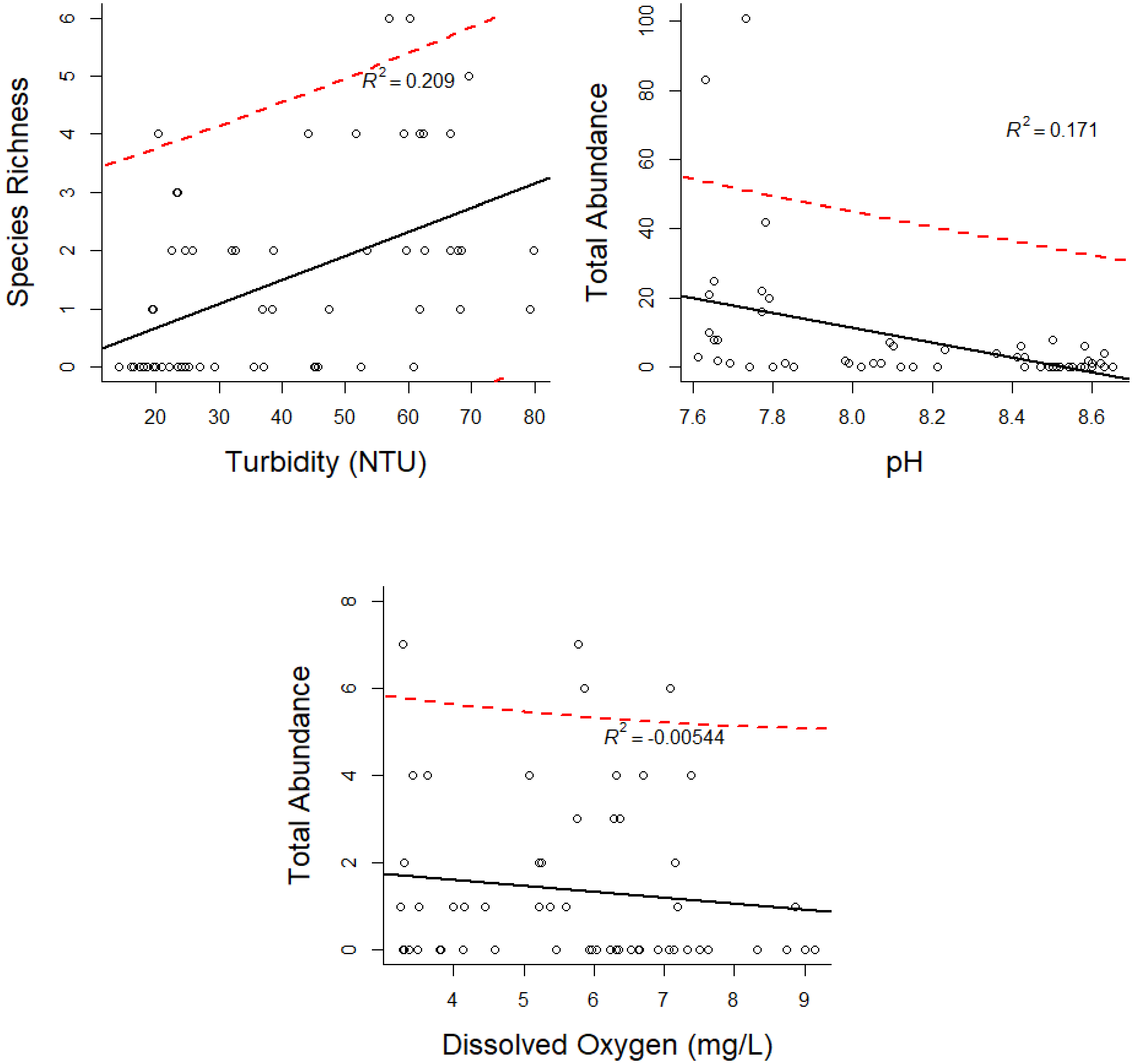
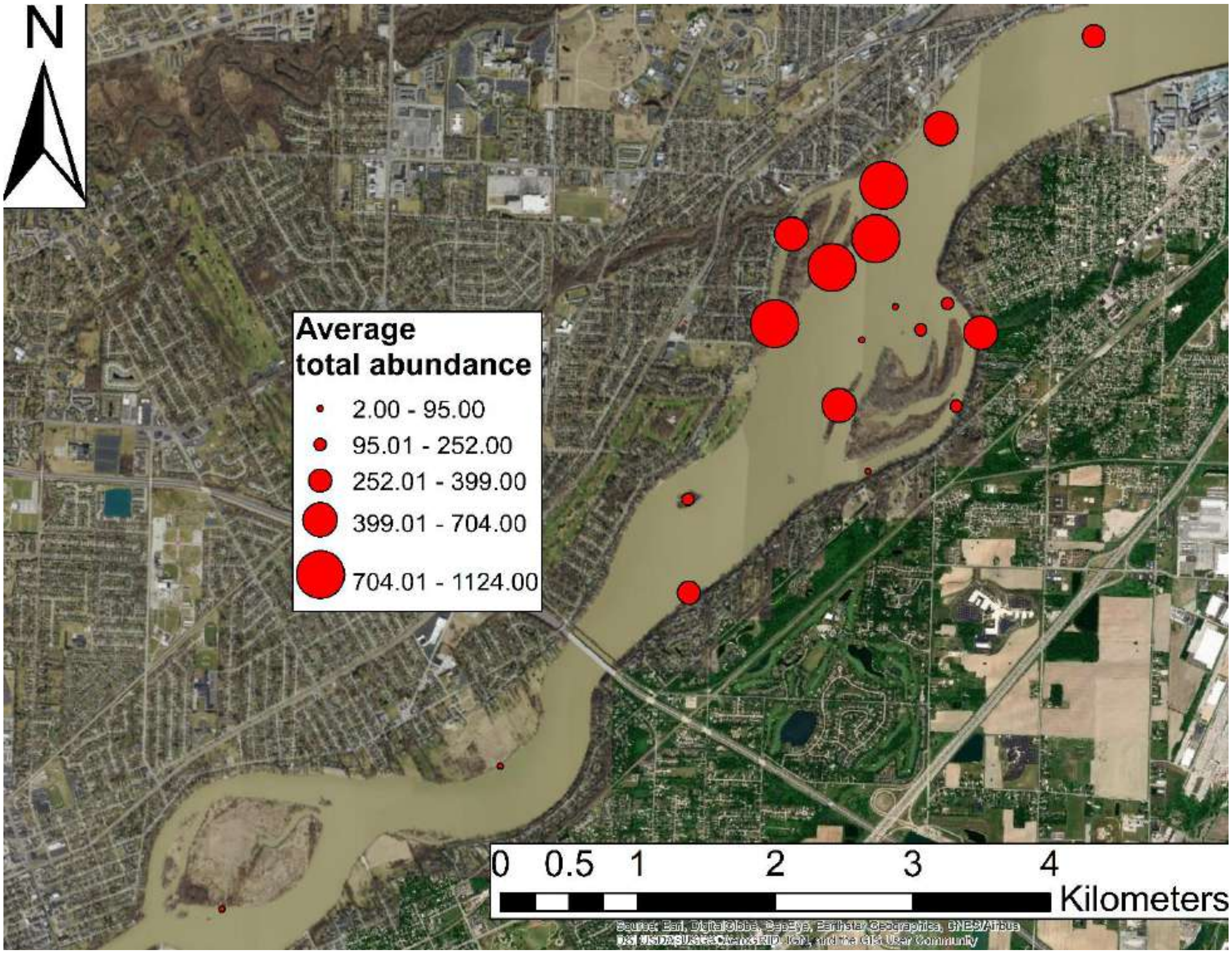


Figure B.5. Species Richness and Total Abundance plotted against variables included in the best AICc models for the mussel trawl dataset (**(A)** Turbidity; **(B)** pH; **(C)** Dissolved Oxygen), solid black lines are fitted logistic regression curves and dashed red lines are 95% confidence bands.

Appendix C: Ponar grab invertebrate data



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure C.1. Total abundance of invertebrates in Ponar grab samples. For areas in which multiple grabs were taken in close proximity, abundance was averaged across grabs.

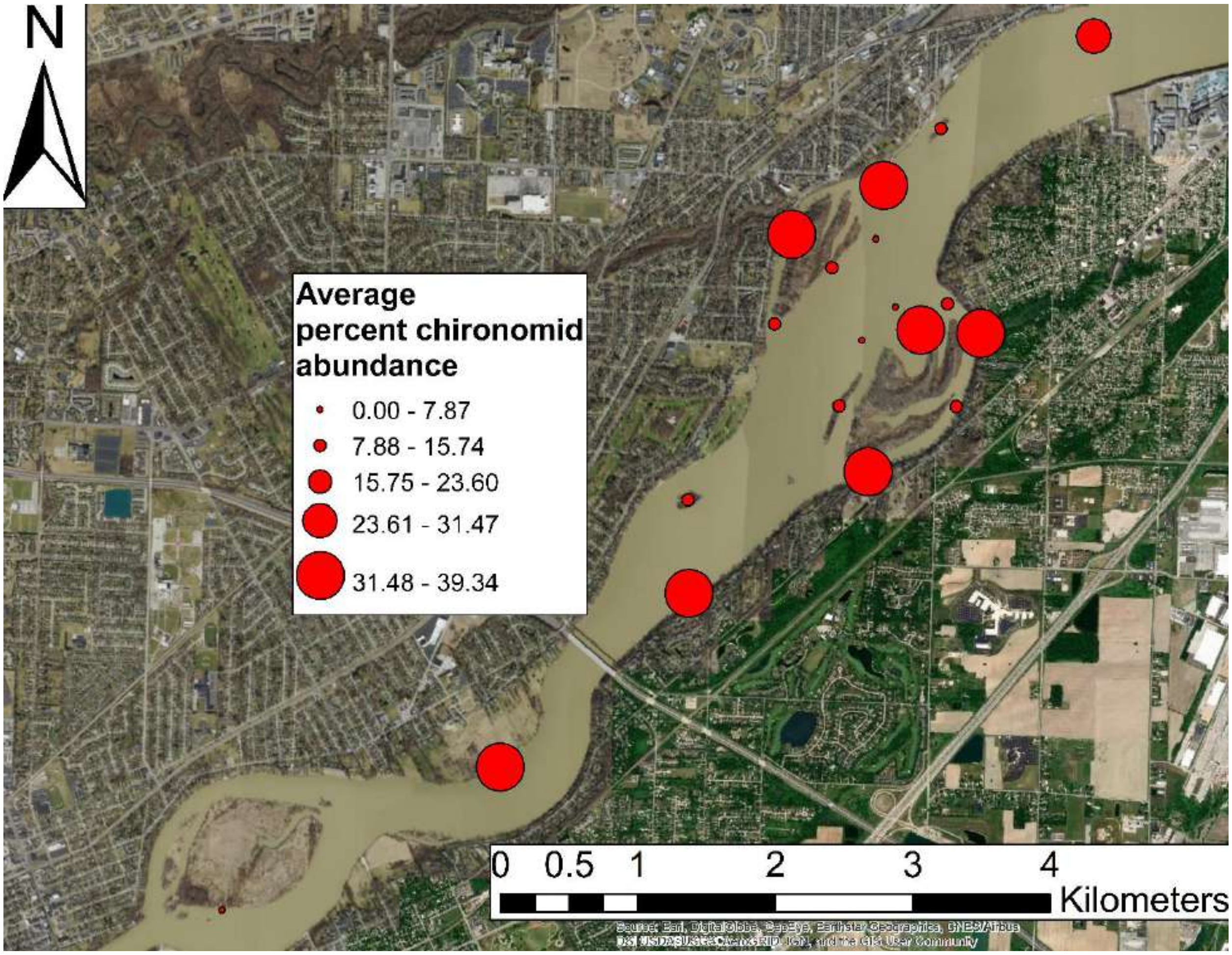
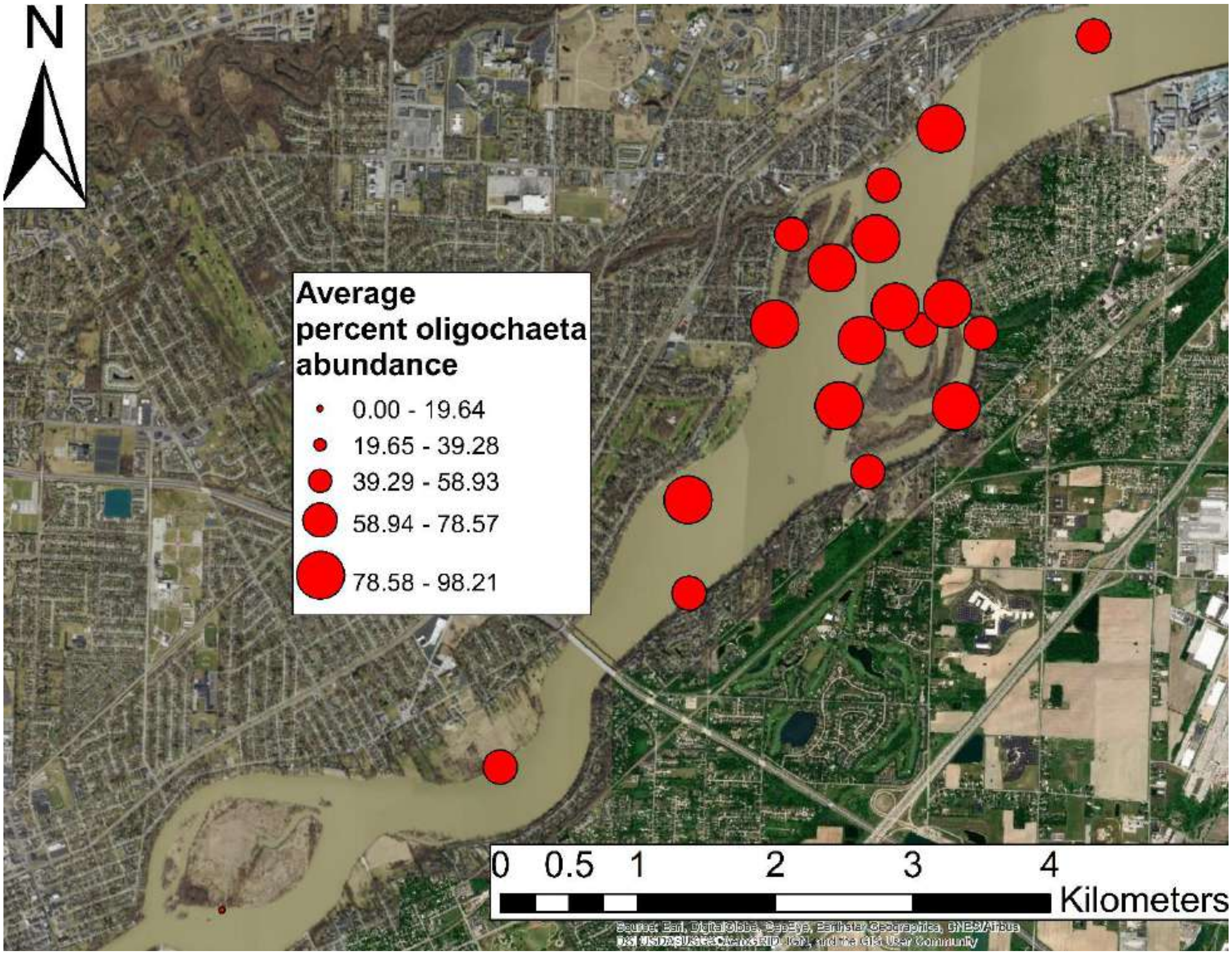


Figure C.2. Percent chironomid abundance in Ponar grab samples. For areas in which multiple grabs were taken in close proximity, percent abundance was averaged across grabs.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure C.3. Percent oligochaeta abundance in Ponar grab samples. For areas in which multiple grabs were taken in close proximity, percent abundance was averaged across grabs.

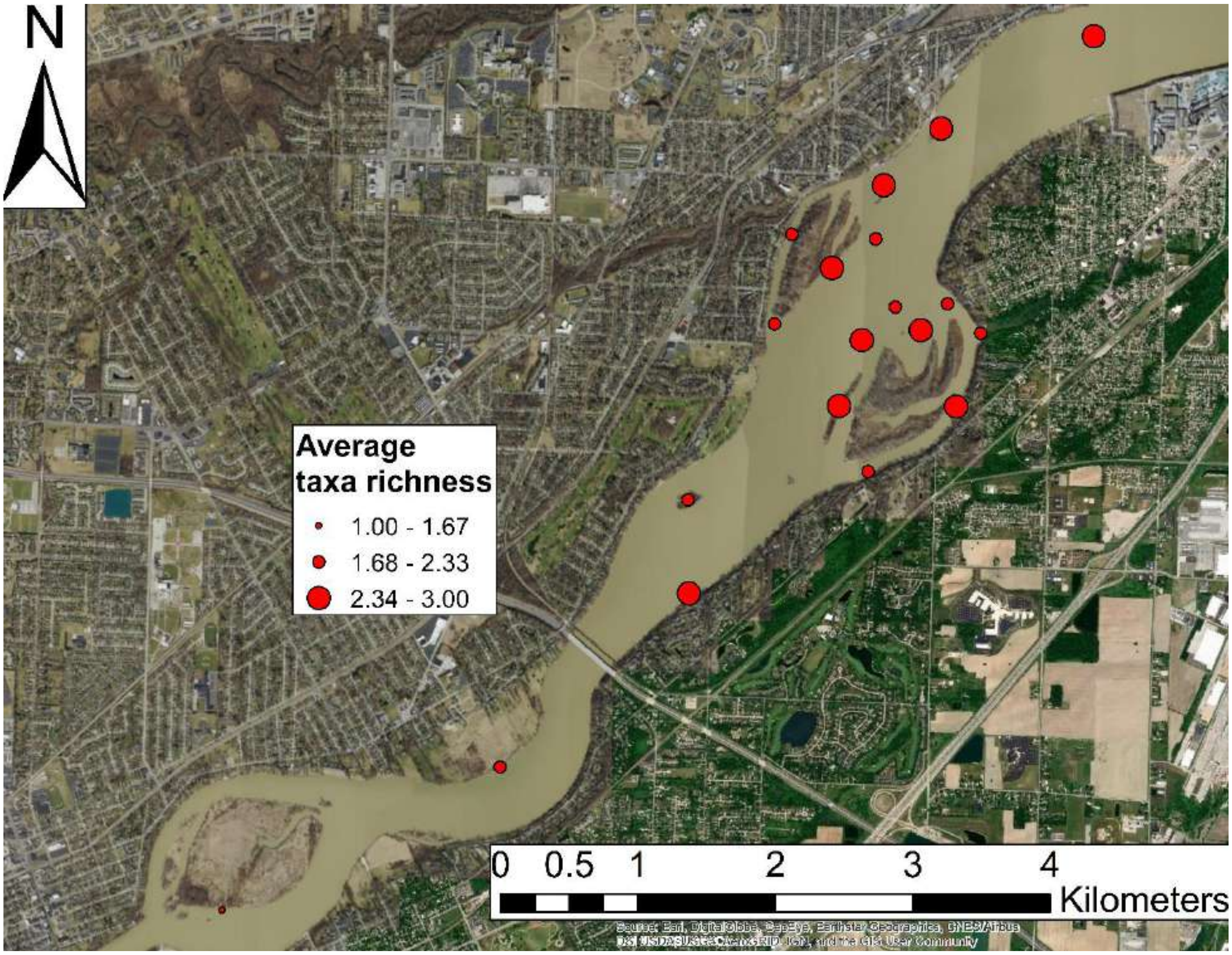


Figure C.4. Taxa richness in Ponar grab samples. For areas in which multiple grabs were taken in close proximity, richness was averaged across grabs.