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Engineering With Nature® (EWN®)

Monitoring the Milwaukee Harbor Breakwater

An Engineering With Nature® (EWN®) Demonstration Project

Eric J. Geisthardt, Burton C. Suedel, and John A. Janssen

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Abstract

The US Army Corps of Engineers (USACE) maintains breakwaters in Milwaukee Harbor. USACE's Engineering With Nature® (EWN®) breakwater demonstration project created rocky aquatic habitat with cobbles (10–20 cm) covering boulders (6–8 metric tons) along a 152 m section. A prolific population of *Hemimysis anomala*, an introduced Pontocaspian mysid and important food source for local pelagic fishes, was significantly ($p < .05$) more abundant on cobbles versus boulders. Food-habits data of alewife (*Alosa pseudoharengus*) and rainbow smelt (*Osmerus mordax*) provided evidence that *H. anomala* were a common prey item. Night surveys and gill netting confirmed *O. mordax* preferred foraging on the cobbles ($p < .05$) and consumed more *H. anomala* than at the reference site ($p < .05$). *H. anomala* comprised a significant portion of the diets of young-of-the-year (YOY) yellow perch (*Perca flavescens*), YOY largemouth bass (*Micropterus salmoides*), and juvenile rock bass (*Ambloplites rupestris*) caught on the breakwater. The natural features' construction on the breakwater increased the available habitat for this benthopelagic macroinvertebrate and created a novel ecosystem benefiting forage fish and a nursery habitat benefiting nearshore game fish juveniles. These data will encourage the application of EWN concepts during structural repairs at other built navigation infrastructure.

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Preface

This study was conducted for the Dredging Operations and Environmental Research (DOER) Program under Work Unit D15GF1 for the Engineer Research and Development Center's Engineering With Nature initiative and was funded by the US Army Corps of Engineers (USACE) Engineering With Nature initiative and the DOER Program. The Program Manager was Dr. Todd Bridges.

This report was prepared by personnel from the US Army Engineer Research and Development Center (ERDC) Environmental Laboratory (EL). This report was written under the direct supervision of Mr. Warren Lorentz, Chief, Environmental Processes and Engineering Division and Mr. James Lindsay, Chief, Environmental Risk Assessment Branch. At the time of publication, Ms. Kathy M. Griffin was Headquarters USACE Acting Navigation Business Line Manager and Mr. Charles E. Wiggins, ERDC Coastal and Hydraulics Laboratory, was the ERDC Technical Director for Civil Works and Navigation, Research, Development, and Technology Transfer portfolio. The Deputy Director of ERDC-EL was Dr. Brandon Lafferty and the Director was Dr. Jack Davis.

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Summary

Through USACE's EWN initiative, along with support from the Great Lakes Restoration Initiative (GLRI), demonstration projects are being implemented to determine whether minor modifications to breakwater repairs can result in improved habitat quality for various aquatic species. These conventional structures currently provide beneficial habitat for fish and wildlife; however, this benefit is an unintentional attribute rather than integral to the breakwater's design. The project in Milwaukee Harbor, Wisconsin was developed to broaden the environmental and social benefits that are provided by the breakwater that were easily integrated as part of ongoing maintenance by making simple, low-cost modifications to the design of the stone used to repair the breakwater.

This report documents a two-and-a-half-year monitoring effort of the aquatic life that utilized the habitat provided by the demonstration project. The objectives of the monitoring effort were to assess physical structure and how it relates to use of the breakwater as habitat by targeted fish species and to assess ecological community that evolves at the structure focusing on fish species of interest and the food web that sustains them.

This research is needed so the benefits being realized by the application of EWN principles at such navigation infrastructure can be understood and appropriately applied at other built structures. With consistent application of such simple modifications during structural repairs, there is tremendous potential to increase multiple benefits associated with built navigation infrastructure.

1 Introduction

1.1 Background

The following section outlines Engineering With Nature® (EWN®) principles and describes the applicability of EWN concepts to support fish and other aquatic life habitat on coastal navigation structures. Applications of modified designs of breakwater repairs are consistent with EWN, a US Army Corps of Engineers (USACE) initiative enabling sustainable delivery of economic, social, and environmental benefits associated with water resources infrastructure (Bridges et al. 2014; Gerhardt-Smith and Banks 2014; Bridges et al. 2018). The EWN concepts addressed through the current project include (1) the use of science and engineering to produce operational efficiencies supporting sustainable delivery of project benefits and (2) the use of natural processes to maximum benefit, thereby reducing demands on limited resources, minimizing the environmental footprint of projects, and enhancing the quality of project benefits (www.engineeringwithnature.org).

USACE maintains responsibility for over 161 km[1] (100 mi[2]) of breakwaters and other coastal navigation structures in the Great Lakes, and EWN concepts have the potential to be integrated with many ongoing projects to provide significant environmental and other benefits as part of ongoing maintenance activities. In 2013, the USACE Detroit District (LRE) began the process of repairing the deteriorated breakwater at Milwaukee Harbor. Repair involves placing armor stone (6–8 metric ton boulders) on the exterior and interior sides of the existing sheet pile–enclosed crib structure.

The LRE typically repairs a section of the breakwater annually as part of its maintenance program. For example, in 2013 repairs involved adding armor stone along the harbor side to about 580 m of the 1950 m long detached breakwater structure. The exterior of the structure has already been repaired in past years. As part of future repair work, LRE is interested in

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 345–7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

evaluating potential environmental enhancements that can be completed by making inexpensive changes to the current design.

The fish habitat creation demonstration project was performed at the Milwaukee Harbor breakwater for multiple reasons. There was an opportunity to add to scheduled operations and maintenance repair at Milwaukee Harbor in spring 2014 through the USACE LRE. This purposely differs from other USACE district demonstration projects in Cleveland where aquatic invertebrate habitat creation was the focus (Fredette et al. 2014) and in Ashtabula Harbor where common tern nesting habitat was created (Fredette et al. 2016). There is also a distinct lack of fish habitat in Milwaukee estuary in general and Milwaukee Harbor in particular, although such habitat was present historically in the estuary. There was keen interest by local stakeholders, especially the Wisconsin Department of Natural Resources (WDNR), for creating fish habitat in the harbor. Finally, the USACE is targeting Great Lakes areas of concern (AOC) to help address beneficial use impairments (BUI) in these areas.

Milwaukee Harbor is a designated AOC by the International Joint Commission. This comes as a result of past urbanization and industrial development which have decreased the habitat value that exists within the Milwaukee Estuary system. The AOC outer boundary extends well out into Lake Michigan and encompasses the entire region around the Milwaukee Harbor breakwater system (figure 1). When an AOC is designated, it is based on a number of BUIs, which form the basis for a remedial action plan (RAP). The demonstration project is intended to support two priorities of the RAP: (1) enhancement of fish and wildlife populations and (2) habitat enhancement.

Success of this project will benefit USACE Great Lakes Districts, the recovery of local native Great Lakes fish populations, and the goals of the WDNR including other stakeholders. Presence of the fish habitat will provide environmental and social benefits through recovery of local fish populations and opportunities for recreational fishing and other aquatic activities.

Additionally, this project demonstrated that EWN concepts could be applied at a Great Lakes breakwater navigation structure. Incorporation of such benefits into USACE projects will serve to reduce social friction, facilitate smoother project implementation, potentially result in overall reduced project costs (as a consequence of reduced social friction), and improve the public image of USACE. In addition, such projects have the potential to contribute to improved ecosystem services and are well aligned with USACE Environmental Operating Principles (http://www.usace.army.mil/Missions/Environmental/Environmental-Operating-Principles/).

1.2 Objective

The objective of the Milwaukee Harbor breakwater fish habitat demonstration project was to determine whether suitable habitat could be created on the Milwaukee Harbor breakwater by making simple, low-cost modifications to the rubble mound used when repairs occur. The design incorporated suitable substrate consisting of the appropriately sized rocks suitable for use as habitat for a variety of native fish and other species. The demonstration was successful in that it provided a means of returning native fish to the harbor. Historically, several native fish spawned in the area but have been largely extirpated from the harbor area due to the loss of suitable habitat. The demonstration will also support plans to use this approach in other locations in the Great Lakes, further contributing to restoration of native fish species throughout their historical habitats.

1.3 Approach

This report documents the modifications made to the project design through selection of stone size and slope as well as documenting the monitoring of the built structure. The design was modified to produce a gentler slope to create fish spawning beds on the interior (harbor) side slope of the armor material. The modified design to create the fish spawning habitat calls for a more gently sloping shelf that is about 1.8 m wide. A smaller grade stone (20–46 cm diameter) was used to construct the shelf, and the gaps between the stones were filled with 10–20 cm diameter cobble (typical of what is found in natural spawning beds). The heterogeneity of the stone sizes and variation in elevation are more reflective of natural reefs and is intended to serve as a spawning bed for lithophilic spawning fish such as walleye (*Sander vitreus*), yellow perch, and smallmouth bass (*Micropterus dolomieu*).

The monitoring of the demonstration project documented the aquatic species utilizing the structure. This was assessed using fiber mesh samplers to collect eggs deposited at the site and the use of video transects. Benthic habitat value of the site was documented through direct sampling of the faunal abundance and also using video surveys. Utilization of the site by juveniles and adult fish was documented through the use of gill nets and the video transects. Other data collected to provide context and interpretation of the biological data were side-scan sonar and photo transects, to establish the as-built condition of the bed and track changes caused by physical forces, temperature regime of the site, and possibly water current conditions.

2 Methods

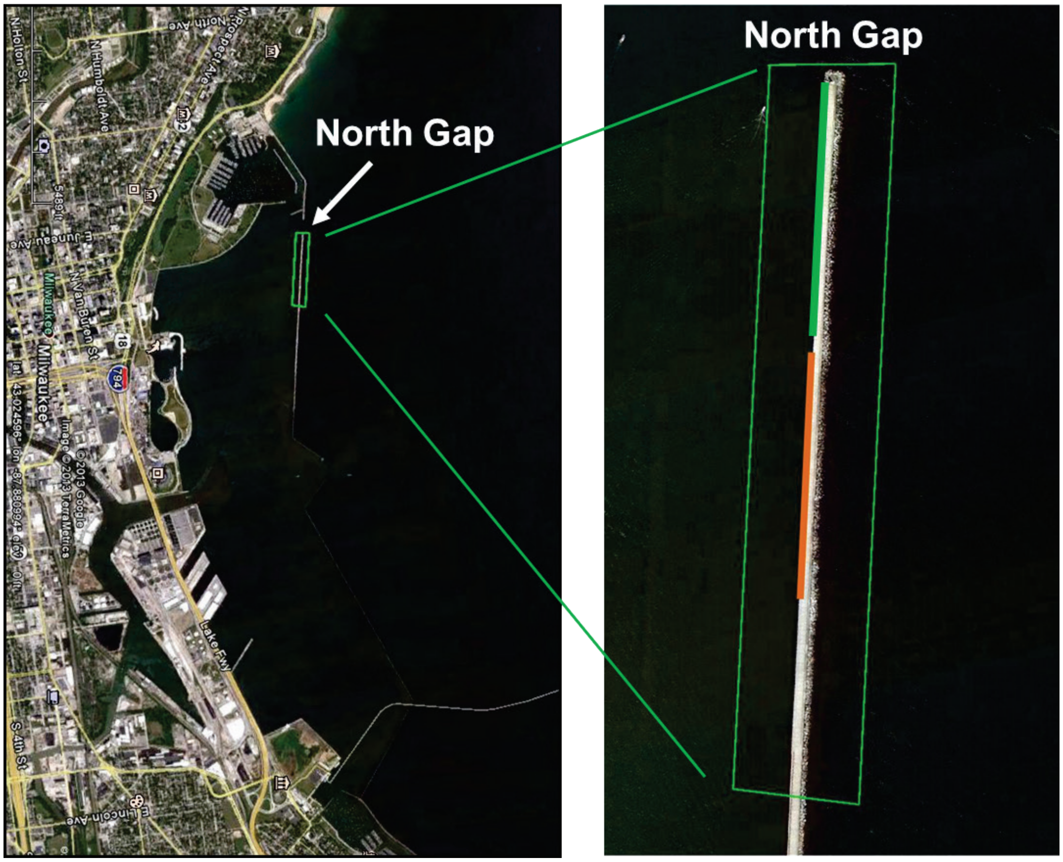
This section outlines the study area and the physical and biological assessments used to monitor the Milwaukee breakwater project.

2.1 Physical assessment

2.1.1 Study area

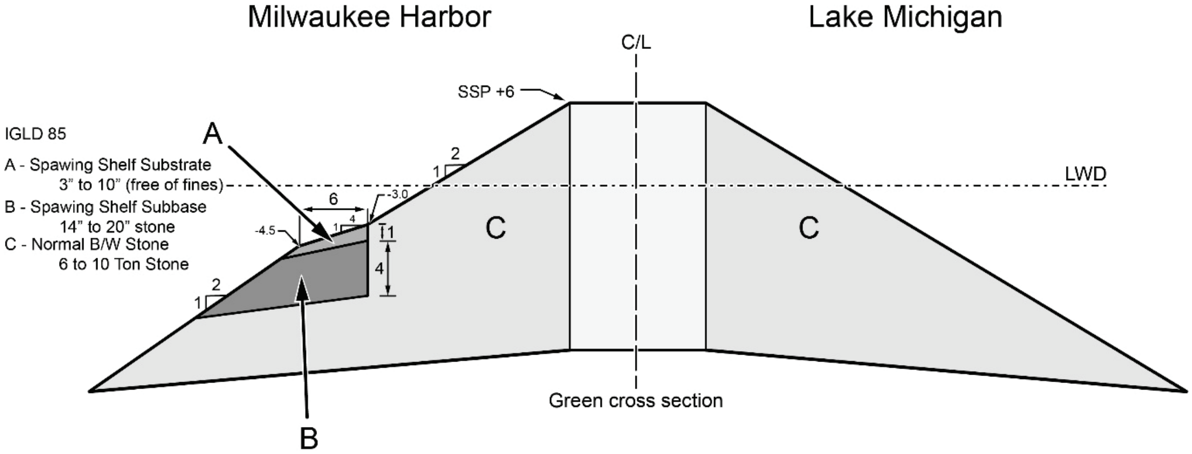
The Milwaukee Harbor green breakwater (GBW) is a section of modified rubble mound breakwater located along the inside of Milwaukee Harbor's outer breakwater, ranging approximately 150–300 m south of the north gap (figure 1). The GBW was constructed using subangular cobble (10–46 cm) to cover boulders (6–8 metric tons) required as structural support for breakwater repairs. The cobble was introduced in April and May of 2014. The top of the cobble is approximately two meters below the water surface, depending on lake levels, and gradually transitions down a slope to a depth of about seven meters where the rock transitions to silty sediment. Original designs (figure 2) called for the cobble to be restricted to a spawning inlay near the top of the reef. However, a majority of the cobble was deposited at a critical angle for slumping, which has resulted in rockslides and periodic shifting due to powerful waves cresting the breakwater during fall and winter storms. During construction, the floating plant crew from the LRE were advised to incorporate ridges and swales, resulting in the heterogeneous habitat at the southern end of the GBW.

Figure 1. Satellite image of Milwaukee Harbor (left) showing the breakwaters that separate the outer harbor from Lake Michigan. The study area (inside green box on right) with the location of the GBW highlighted in orange and the reference site (REF) highlighted in green.



The reference site (REF) is the north adjacent section of boulder breakwater inside the harbor which was repaired using placement of rubble mound stones in 2013. This stone was deposited at the same time that the boulders underlying the GBW veneer were installed. This REF was selected as reference habitat due to the likelihood of experiencing similar hydrologic and thermal conditions throughout the season. The anticipated currents and temperature regime were to have a significant influence on the fish species utilizing of the breakwater. To the south of the GBW is also rubble mound stone, but most of this was deposited later in 2015 and 2016.

Figure 2. Cross section of the plan for construction of the GBW and fish spawning inlay. *C* indicates standard 6–10 metric ton stone boulders.Cobble *B* used to replace stone includes 20–46 cm stone, and the habitat inlay *A* comprised of 10–20 cm stone at the top of the reef. Mean lake elevation is indicated by the dashed line. (Drawing Credit: Cathryn Gear).



Physical assessment of initial construction was conducted in 2014 via multibeam sonar bathymetry by the USACE. In August of 2016, a second assessment of the GBW was conducted by the University of Wisconsin–Milwaukee (UWM) using a Lowrance HDS-10 Gen 2 with StructureMap High-Definition Sonar Imaging during aquatic habitat mapping efforts in the Milwaukee Harbor (see section 3.1). Observations and measurements of physical dimensions of the GBW and REF were also made by divers in 2016.

Figure 3. Milwaukee Harbor Breakwater, 4 April 2014, showing the GBW in its early construction, which was initiated at the north end.

2.1.2 Temperature

Temperature loggers (HOBO Water Temp Pro V2 data logger) were deployed at the north and south ends of the GBW in May 2015. Data loggers were exchanged via scuba diver or snorkeler in October 2015, and again in June 2016, to download data and redeploy. Each string of temperature loggers consisted of a shallow logger at two meters, a middle logger at four meters, and a bottom logger at the base of the reef in seven meters of water. Loggers were individually attached to a lead-core line fastened to the breakwater and buried under the cobble to prevent snagging by anglers. Burying the loggers also prevented the shallow loggers from being influenced by solar radiation, which would have skewed daytime temperatures. Data loggers recorded at five-minute intervals during summer months to capture fine-scale details of upwelling and seiche events. Over winter, when the lake was no longer stratified, loggers recorded at one-hour intervals.

2.2 Biological assessment

2.2.1 Fish sampling

This assessment inventoried fishes occurring near the breakwater and collected food-habits data to help construct a food web model. Fish use of the GBW and REF was monitored biweekly via gillnetting from June through October in 2014 and 2015. In 2015, experimental gill nets (EGN) with a range of mesh sizes (63.5 mm, 50.8 mm, 38.1 mm, 25.4 mm, 12.7 mm) were used. The panels were 30 m in length for each mesh size. Each panel was 1.3 m high for a 150 m total length to catch a wide range of fishes. At the end of 2015, a concern was raised by the authors that EGN were lethally sampling the most abundant resident fishes, mainly rock bass, in high numbers, which might significantly impact the assessment of their utilization of the reef. Consequently, in 2015, two night dives were conducted to determine whether these might suffice for assessment of primarily rock bass. The monitoring effort in 2015 also strongly suggested that the invasive opossum shrimp, *Hemimysis anomala,* was the most important forage for a diversity of smaller nonresident species, especially alewife (*Alosa pseudoharengus*) and rainbow smelt (*Osmerus mordax*), which appeared to be highly attracted to both the GBW and REF.

Consequently, in 2016, two sizes of micromesh gill nets (8 mm and 6 mm stretch, 1.3 m height, 61 m total length) were utilized to target juvenile alewife (year class 2015), and other juvenile fishes as it was observed that the GBW was likely serving as nursery habitat. During the final five nettings of 2016, an additional 15 m long gill net panel of 12.7 mm stretch by 1.3 m height was fished with the graded micromesh nets. This mesh captured alewife, rainbow smelt, and yellow perch too large for the 8 mm stretch mesh during the summer of 2016.

Sampling locations were the same for all nets set at the GBW and REF over the course of both the 2015 and 2016 field seasons. Nets were set along the rocky slope in approximately 3 m of water. All gill nets were fished overnight from approximately 1600 to 0800 and pulled in the same order as they were deployed to ensure equal sampling times. Nets were pulled by hand and both fish and nets immediately covered with ice in separate bins. Captured fish were promptly removed from the net and live fish euthanized with an overdose of tricaine methane sulfonate, also known as MS-222. Fish were identified to species, enumerated, and the standard and total length to the nearest millimeter was recorded from a subsample of up to 10 fish per species per site. For food-habit analysis, a sample of fish were preserved in 95% ethanol.

Gee-minnow traps, baited with dried dog food pellets, were used in 2015 to sample round goby (*Neogobius melanostomus*) and crayfish relative abundance at both the GBW and REF, with five traps per site. Round gobies were too small to be adequately sampled by EGN but are well sampled by micromesh gill nets, and their catch-per-effort correlates well with visual and video strip-transect assessments (Houghton and Janssen 2015). The minnow traps were not used in 2016, in part because round gobies caught in baited traps would likely have biased stomach samples.

2.2.2 Food-habits data

The breakwater was sampled by gill netting in 2016. Analysis of stomach contents from gill-netted fishes was used to examine the developing food web of the GBW and REF areas and address whether foraging behavior or diet was different among fishes caught at the two sites. Following each gill net set, a subsample of ten fish per species per site were separated for stomach content analysis and preserved in 95% ethanol. If fewer than ten fish of a species were harvested, then all stomachs were removed for analysis. Contents were analyzed under a dissecting microscope, enumerated, and each item was identified to the lowest practical taxon. In the case of round gobies, which lack a defined stomach, the entire digestive tract was examined.

2.2.3 Benthic sampling (rock collections)

Whole rock collections were made in late September 2015, July 2016, and early October 2016 to assess changes in the benthic invertebrate community on the newly placed cobble on the GBW. Due to the lack of collectable-sized rocks present at the boulder REF, no samples were taken there. Similar-sized rocks (8–20 cm) were collected by scuba divers on all three occasions by quickly sealing the rock in a cloth bag fastened shut with a cable tie. Individual rocks were taken nonvisually by probing with eyes closed for rocks that could be quickly bagged. A total of 12 rocks was collected during each sampling event; however, one rock was misplaced in October 2016, and only 11 were processed. These samples were processed by rinsing each rock and its bag over a 500 µm sieve to capture benthic macroinvertebrates attached to the rocks and mussel matrix. Each rock was also scraped clean of any mussels and accompanying macroinvertebrates, which were then preserved in 95% ethanol for identification and enumeration. Samples were sorted and processed under a dissecting microscope, then identified to the lowest practical taxon.

2.2.4 *Hemimysis anomala* traps

A novel funnel trap was developed for sampling *H. anomala* in rocky habitats that also functioned effectively at a variety of substrates, depths, and population densities. Colleagues (Dr. Bart DeStasio of Lawrence University in Appleton, Wisconsin and Dr. Scott McNaught of Central Michigan University in Mt. Pleasant, Michigan) have established that vertically towing plankton nets adjacent to dock walls after the nets have lain several minutes on the bottom is an effective way to capture this mobile lithophilic mysid. This methodology may be effective when *H. anomala* exhibit swarming behavior at high population densities or in habitats lacking diverse cavities (that is, dock walls). However, it is neither effective nor practical in rocky habitats or shallow water, at low population densities, or early in the season when swarming behavior is exhibited infrequently. In 2015, a simple funnel trap in a coffee can was developed which was initially successful, but the funnel opening too often became fouled with sloughed *Cladophora* and rust. Redesigned traps in 2016 consisted of a black 7.6 L bucket with a large funnel affixed inside and a lid with a 15 cm diameter hole cut into it. The tip of the funnel was trimmed back to leave a 2 cm diameter opening into the bucket to alleviate fouling. A window-sash weight was affixed to the bottom of the bucket to ensure traps would remain in place. Traps were deployed by divers or snorkelers who excavated a hole in the cobble for the bucket and ensured the weight and trap were firmly fixed in the substrate. Deployments were made on the same day as gill net sets with five traps on the GBW and five at the REF. Captured *H. anomala* were sorted into juveniles, adult males, and adult females to assess population structure. Several *H. anomala* stomachs and fecal pellets were examined in September 2015 and September 2016. Their contents were examined to generate a preliminary diet but not enumerated, as few hard structures remained intact.

Floating emergence traps for sampling midges emerging off the breakwater were set eight times between early August and October 2015. Sets of four traps were set on the REF, GBW, and 2 to 3 m off of the original sheet-piling wall as a control. Emerging midge pupae are an essential food source for many fish in Milwaukee Harbor and help connect the increased benthic productivity to the pelagic food web.

2.2.5 Night dives

Night scuba dives were conducted twice in 2015 and seven times in 2016. The first night dive (7 July 2015) was exploratory and investigated the behavior of *H. anomala*, which was appearing in diets of rock bass and alewife but not seen during daytime dives until late July 2015.

In 2016, a protocol was established for recording standardized observations along paired transects. During night dives, a pair of divers with identical dive lights worked together, one diver surveying a shallow transect (<4 m), and the other diver surveying a deep transect (>4 m to base of rocks). Transects consisted of five 30 m sections marked with submerged buoy lines on both the GBW and REF for comparison. At the end of each 30 m segment divers surfaced and recorded the number of all fish species and crayfish observed, along with any other notes. The direction that transects were run (north or south) was determined randomly, as was the deep vs. shallow diver. Video was taken with the GoPro Hero2 for documentation of fish and invertebrates. Alewife numbers were not recorded during night dives, as their high mobility and schooling nature made counting difficult and distinguishing between the same fish multiple times impossible.

2.3 Statistical analyses

All analysis of variance (ANOVA) analyses were run using SYSTAT 10.2 and paired *t*-tests were conducted using Microsoft Excel.

2.3.1 Fish sampling

Two-factor ANOVA was used to compare log(n+1) transformed round goby catches from minnow traps at both sites with site and date as the independent variables. This also tested for the effect of site and date interactions as well as each of these main effects.

Two-factor ANOVAs were also used to compare log(n+1) transformed gillnet catches from 2016 of round goby, rainbow smelt, alewife, and yellow perch, as these species were the only ones caught on enough dates for comparison. For these tests, site becomes the fixed independent variable, and date becomes the random replicator due to variations in environmental conditions.

A paired *t*-test was also preformed comparing the total lengths of rock bass caught at the GBW and REF.

2.3.2 Stomach contents

To analyze the consumption of *H. anomala* by alewife, rock bass, and rainbow smelt in 2016 at each site, two-factor ANOVAs were conducted with site and date as independent variables and the log(n+1) transformed number of *H. anomala* consumed as the dependent variable to determine differences in foraging between the sites. This tested for the effect of site and date interactions as well as each of these main effects. Individuals with empty stomachs and dates without paired fish samples were excluded from analysis.

To assess the overall diet composition and foraging preferences in commonly encountered fish, frequency of occurrence (%F_i) and numeric proportion (P_i) were calculated,

$$\%F_i = \left(N_i / N\right)\times 100 \tag{1}$$

therefore,

$$P_i = S_i / S \tag{2}$$

Where N_i equals the number of a species with food item *i* in their stomach and *N* equals the total number of fish with stomach contents, and S_i equals the total combined number of food item *i* in the stomachs of a species and *S* equals the total combined number of all food items consumed by that species.

Juvenile alewife <90 mm total length (TL) were separated from larger adults for the purposes of stomach analysis, as these smaller fish were all likely less than one year old. The 90 mm cutoff for juveniles was established because the length histogram of dissected alewives indicates a tightly grouped year class at this length. Additionally, 90mm was also the maximum size reached by a known-age alewife of the 2015 year class before YOY from 2016 first captured by nets. Because not all alewife were aged, no statistical analyses were run to compare age <1 year alewife to adult alewife.

2.3.3 *H. anomala* traps

Two-way ANOVAs were run on the contents of *H. anomala* traps set during 2016 with site and date as independent variables and log(n+1) transformed *H. anomala* catch divided into five subcategories of total, juvenile, adult, male, and female, each analyzed as dependent variables. This tested for the effect of site, date, and site and date interactions for each of these independent variables.

2.3.4 Night dives

The number of rock bass and rainbow smelt observed during night dives at each site was used to conduct a three-factor ANOVA with site, date, and depth as independent variables. This tested for the effect of site and date, site and depth, date and depth, and date and depth and site interactions as well as each of these three main effects.

2.3.5 Whole rock samples

A one-way ANOVA was run on the invertebrates sampled from rocks at GBW with date as the fixed independent variable and invertebrate counts as the dependent variable. Invertebrate classes included chironomid larvae, amphipods (*Echinogammarus ischnus*), and quagga mussels. Total volumes were measured for each rock, and the number of quagga mussels for each rock was counted; the ratio of total volume and number of mussels was then used to estimate average mussel size per rock. A post-hoc Tukey's honestly significant difference test, a multiple comparison test also known as Tukey's HSD test, was used for pairwise comparisons.

3 Results

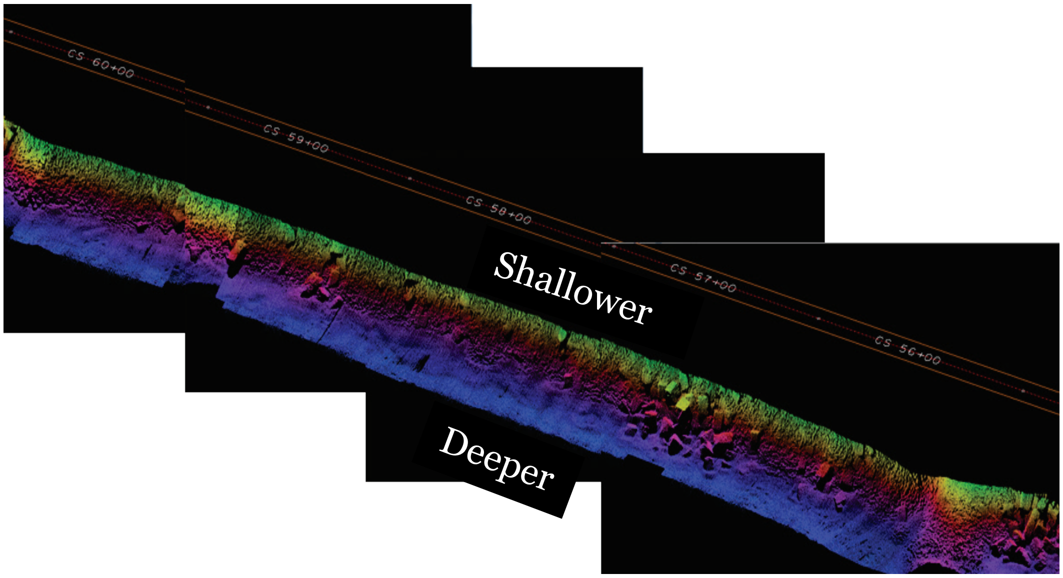
3.1 Physical assessment

The completed structure of the GBW did not remain intact (figure 4A–B) because the small and medium cobble inlay migrated slightly due to storm-induced wave energy, slipping downwards to the base (figure 5A–B). In its current configuration, the cobble now forms a veneer over the armor stone. This is apparent from the multibeam sonar scan conducted during summer 2014 (figure 5A–B). Consequently, the GBW cobble provides numerous small cavities from its summit, at about 0.5 m depth, to the bottom, at 7 m. Near the surface are submerged caves between the armor stone. Because the Lake Michigan water level has risen about 0.5 m since the GBW was constructed in spring 2014, the previously exposed armor stone is now partially submerged (figure 6). The top of the deposited cobble has also lowered, indicating slumping. Cobble intended for the inlay tumbled down the boulders, forming a veneer of cobble to the base at 7 m. The cobble is typically at its critical slope angle so it is unstable. This often means that sampling deployments slide down the cobble. Consequently, vulnerable deployments were tied to the sheet piling. The most clear-cut evidence of slumping derives from the partial burial of a weighted transect line that was deployed in summer 2015 and rested on the cobble at about 1 m depth near the transition from armor stone to cobble. By 2016, much of the line was either buried under cobble at some unknown depth or at the cobble surface as much as 3 m downslope.

The rise in the Lake Michigan water level is most likely due to two cold winters (2013–2014 and 2014–2015; see: https://www.glerl.noaa.gov/pubs/brochures/lakelevels/lakelevels.pdf) allowing ice to form over much of the lake, greatly reducing evaporation. When the cobble was deposited in spring 2014, it was near the water surface, with exposed boulders adjacent to the sheet piling almost entirely above the water. The higher water levels partially covered normally exposed boulders, producing numerous flooded caves that were subsequently occupied by fishes.

Figure 4. Two multibeam sonar images.

A. Multibeam sonar image of the GBW. Some basal armor stone is protruding at about breakwater marker 57+00. For comparison of the texture of the REF see figure 5B.



B. Multibeam sonar image of the REF immediately north of the GBW. The length of this section is about 152 m, nearly identical to the length of the GBW.

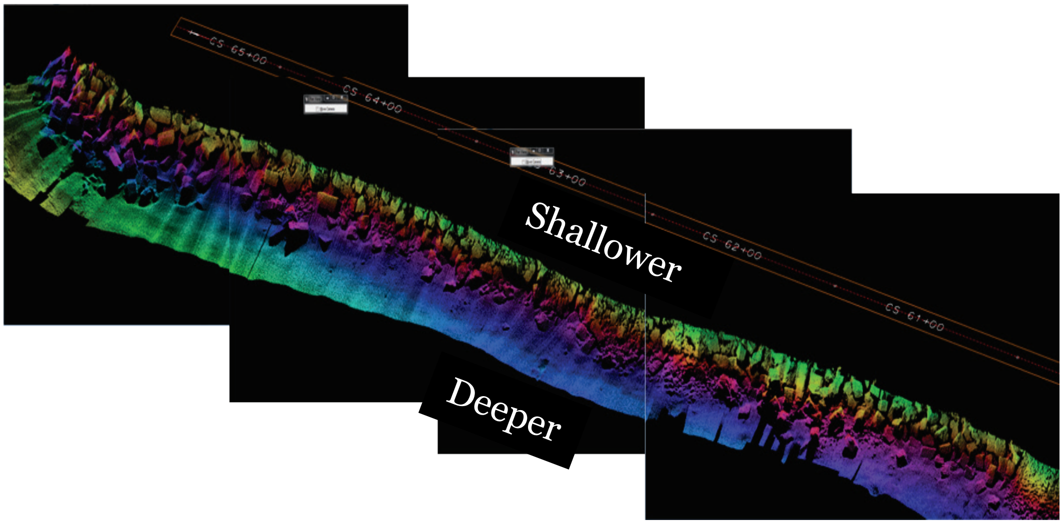
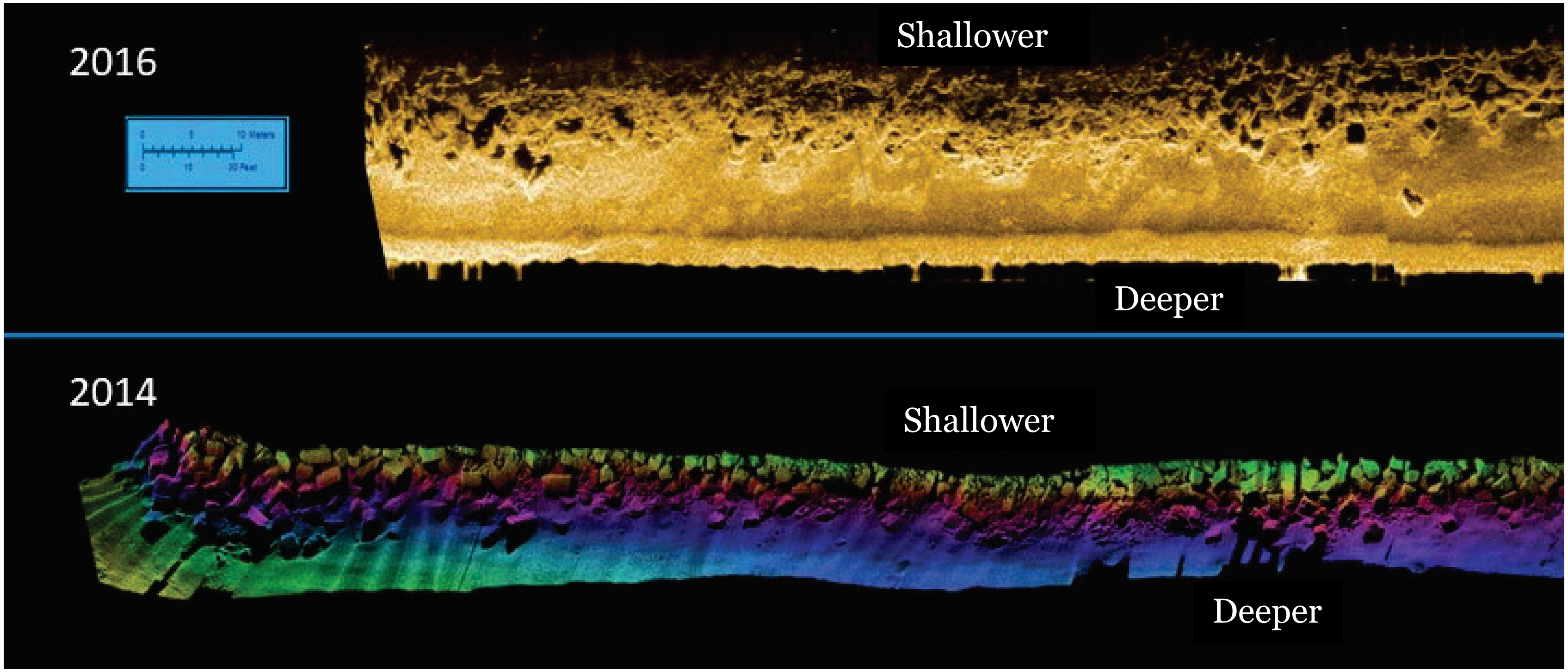
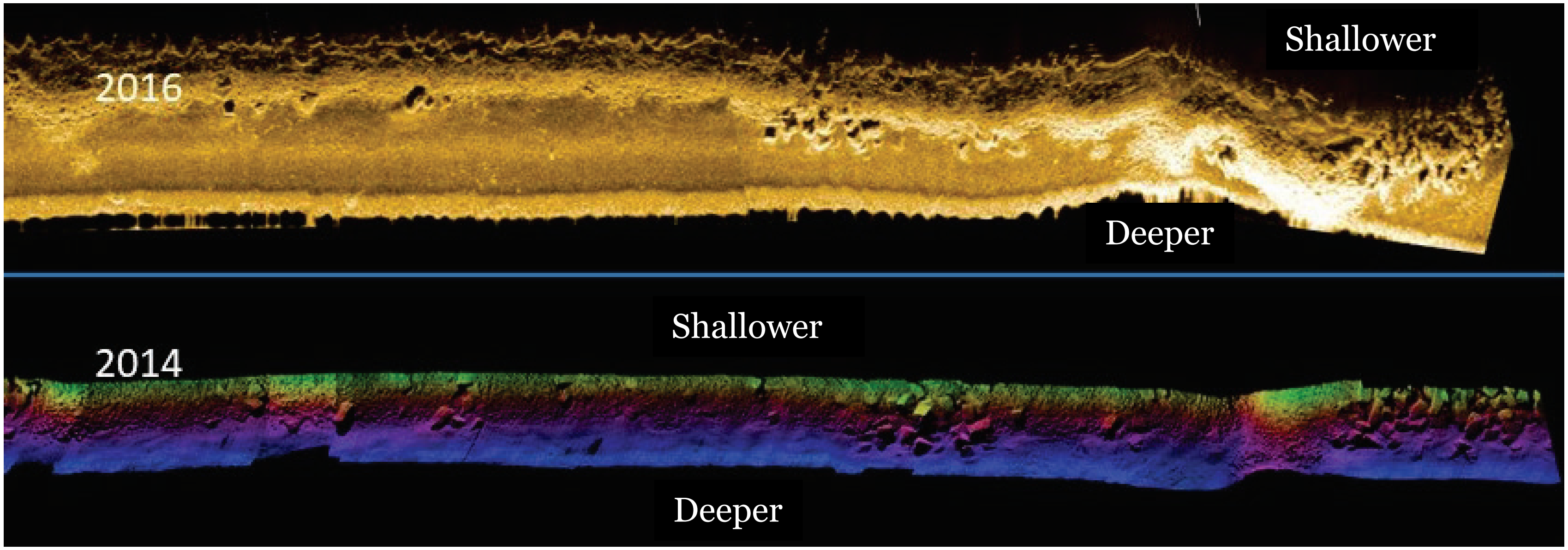


Figure 5. Two multibeam sonar images.

A. A comparison at the REF of initial construction in 2014 via multibeam sonar bathymetry by USACE (bottom) and in 2016 via sidescan sonar by Brennan Dow (top) using Lowrance HDS-10 Gen 2 with StructureMap HD Sonar Imaging. Minimal to no changes were found apparent in the reference section.



B. A comparison of the GBW section of the initial construction in 2014 via multibeam sonar bathymetry by USACE (bottom) and in 2016 via sidescan sonar by UWM (top) using Lowrance HDS10-Gen 2 with StructureMapTM HD Sonar Imaging. Changes on the GBW between 2014 and 2016 are in https://www.glerl.noaa.gov/pubs/brochures/lakelevels/lakelevels.pdf.



3.1.1 Ancillary observations

In September 2015 a section of the breakwater was sampled that had not yet had boulders placed alongside the deteriorating sheet piling, south of the GBW and south of where fresh armor stone was being deployed by USACE. Observations of what was underlying the sections shown in figures 5a and 5b was desired (mostly deteriorating sheet piling). Qualitative observations indicated scattered boulders and other debris that were covered with quagga mussels as well as the presence of numerous round gobies. *H. anomala* were found but did not appear to be nearly as abundant as on the GBW, an observation that was a focus of further sampling in 2016 (see Section 3.3.1.2).

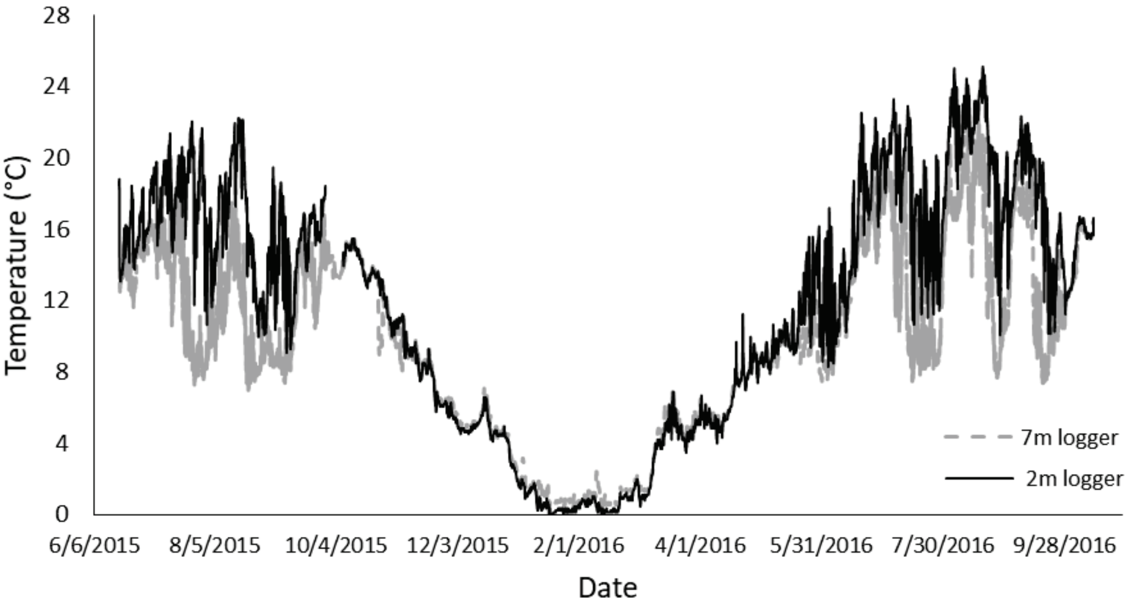
Figure 6. A typical section of the GBW shortly after the stone had been deposited in April 2014. The black line approximates the water level for summer 2015 and 2016, which is about 0.5 m higher. Currently there are numerous caves created by the boulders being inundated; these caves were absent at the time of construction. The caves served as hiding places for diverse fishes to catch prey among the adjacent cobble (Photo: Tom Fredette, USACE).

3.2 Temperature

Water temperatures were mostly cold (20–25 °C) for summer then warm in the autumn of 2015 (8–16 °C; figure 7). In 2016 summer temperatures varied and were neither consistently warm nor cold. The 2015 cold summer water temperatures were due to persistent south and southwest winds that push the Lake Michigan epilimnetic water offshore. Summer 2015 had one of the most extreme and extended periods of upwelling: while midlake surface temperatures were typically about 19–21 °C, the GBW temperatures rarely exceeded 20 °C and were sometimes as low as 10 °C.

Temperature fluctuations at the GBW were of concern because of its proximity to the north gap, making it quite vulnerable to upwelling events, which cause rapid changes in water temperature. These mixing water masses have the potential to cause significant changes in fish behavior, feeding, and depth distribution (Magnuson, Crowder, and Medvick 1979; Brandt, Magnuson, and Crowder 1980). Paired deep and shallow temperature loggers deployed from June 2015 to October 2016 indicated that the thermal regime at REF and GBW varied by less than 2 °C at all times throughout the course of the study. Upwelling events were frequent in both years, and in 2015 were sometimes prolonged for several weeks. The intensity of upwelling varied but at times, in both years, caused temperature fluctuations of 12 °C over 24 hr periods. A historically intense upwelling during late August 2015 dropped surface temperatures throughout the harbor from 22 °C to 8 °C for several consecutive days (figure 7). This caused most fish to vacate or become inactive.

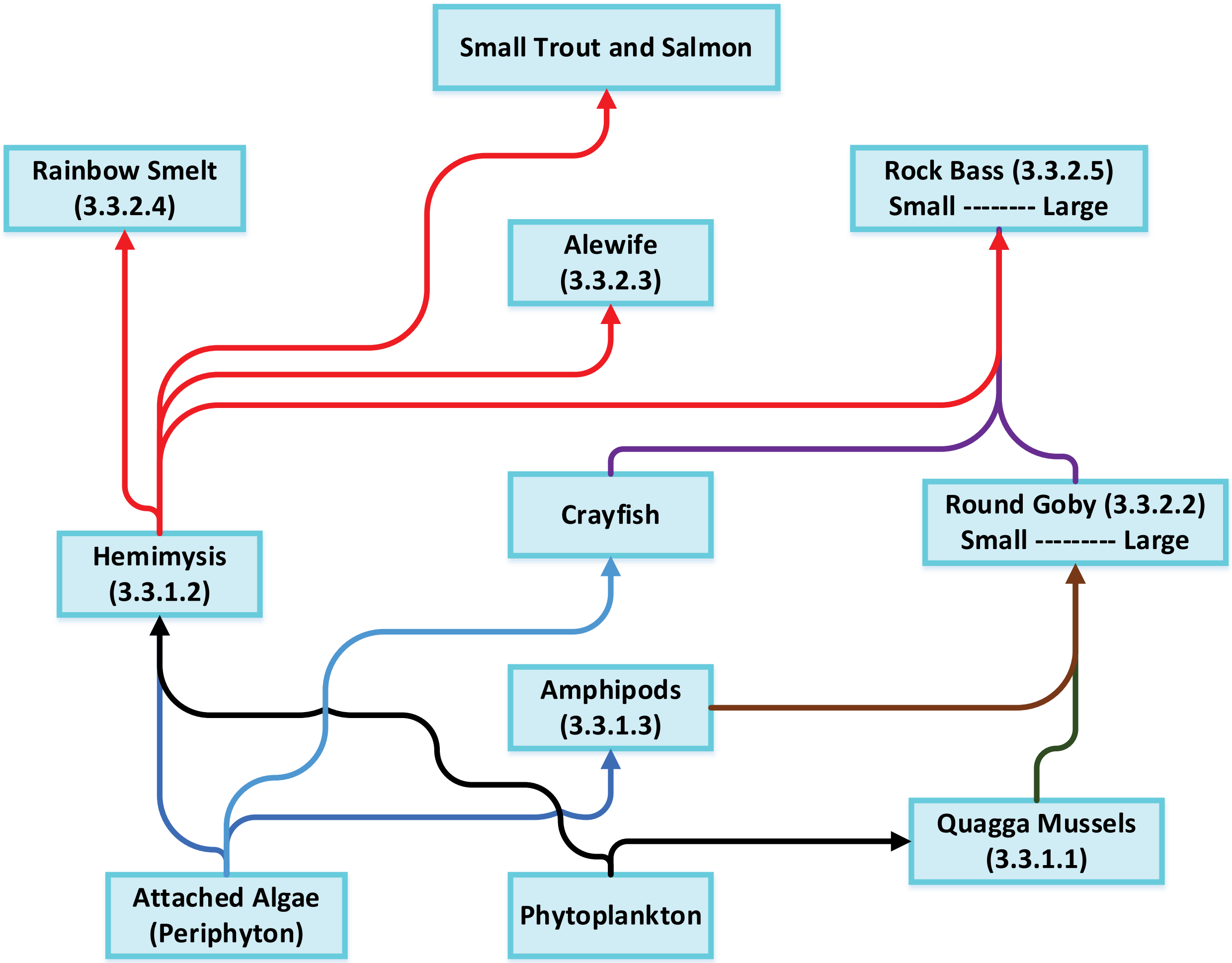
Figure 7. Temperatures recorded by HOBO pendant temperature loggers at depths of 2 m (black line) and 7 m (gray line) at the northern edge of the GBW. Note that in both summer 2015 and 2016 there are wide temperature fluctuations corresponding to coastal upwellings and downwellings.



3.3 Biological assessment

This section focuses on the major components of the GBW and REF food web (figure 8). The primary forage for small fishes included amphipods, an invasive mysid shrimp (*H. anomala*) and quagga mussels (prey for round gobies only). The fishes were primarily a mix of coastal species (that is, rainbow smelt, alewife, small brown trout, and rainbow trout) and rock bass, which are restricted to Milwaukee Harbor and its tributaries. Experimental gill nets occasionally captured large brown trout and walleye. Adult smallmouth bass were commonly seen during snorkel or scuba dives. While too few prey samples were recorded for a definitive description of their role in the food web, the primary prey of the larger brown trout, walleye, and smallmouth bass in the captured fishes were alewife and round goby.

Figure 8. Proposed food web featuring the species most consistently observed on the reference (REF) and green breakwater (GBW) sections of the breakwater in Milwaukee Harbor.



3.3.1 Forage

3.3.1.1 *Dreissenids (primarily quagga mussels,* Dreissena bugensis*)*

Dreissenids showed statistically distinguishable total sample volume differences (log10 transformed, one-factor ANOVA, $F_{2,32} = 38.45$, $p < .001$), numbers of mussels (log10 transformed, one-factor ANOVA, $F_{2,32} = 58.38$, $p < .001$), and average volume per mussel (one-factor ANOVA, $F_{2,32} = 8.54$, $p < .001$). The post-hoc Tukey tests indicated that mean total volume of mussels decreased significantly ($p < .001$) from September 2015 to July 2016 then increased significantly ($p < .001$) by October 2016. The mussel mean numbers decreased between September 2015 to July 2016, then remained stable ($p = .17$). Mean volume of individual mussels was not statistically distinguishable between September 2015 and July 2016 ($p = .96$), but mussels were significantly ($p = .004$) larger between July and October 2016. The decrease in mean number from 2015 to 2016 was likely due to predation by round gobies, an impact that has been demonstrated elsewhere (Lederer, Massart, and Janssen 2006; Lederer et al. 2008). The increase in volume from July to October 2016 is likely due to growth of surviving individuals that were now too large to be consumed by round gobies (Lederer, Massart, and Janssen 2006; Lederer et al. 2008).

3.3.1.2 H. anomala

H. anomala was the most obvious forage animal seen during snorkeling or scuba operations as well as in preliminary diet analyses. All sizes were, generally, most abundant on the GBW section compared to the REF, (figure 9) which pools all sizes and life stages. Two-factor ANOVAs run on the four categories of adult, juvenile, male, and female *H. anomala* indicated there were significant effects of site and date on adult and male but not juvenile or female *H. anomala* (table 1). Because of the significant interaction terms, site and date cells were compared via Tukey tests, which indicated that GBW traps averaged consistently greater numbers of *H. anomala* when compared to the REF. Thus, the statistical significance of the site factor is meaningful, and the results show that the smaller rock veneer at the GBW had higher densities of *H. anomala*. A possible mechanism is more available and more complete cover when compared to REF. The cobble-filled gaps in the underlying armor stone provided an abundance of small gaps as shelter.

Bycatch of *H. anomala* in traps was extremely low (0.007%) and consisted of only round goby fry, juvenile rusty crayfish (*Orconectes rusticus)*, and *Echinogammarus ischnus*. Only 1 trap out of 119 total sets was fouled with sloughed *Cladophora*.

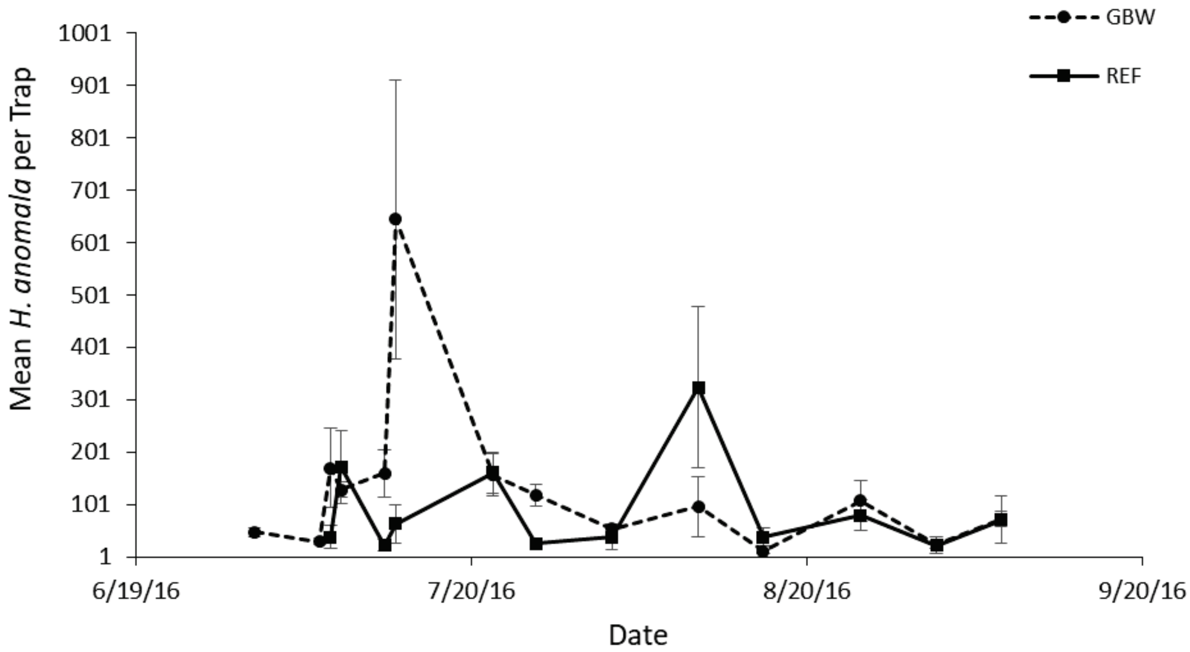


Figure 9. Total (all size and sex categories) *H. anomala* per trap by date.

Table 1. *H. anomala* trap two-factor ANOVA results.

	Total *H. anomala*		Adult *H. anomala*		Juv *H. anomala*		Male *H. anomala*		Female *H. anomala*	
Site	$F_{1,84} =$	6.805	$F_{1,84} =$	5.567	$F_{1,84} =$	6.230	$F_{1,84} =$	8.347	$F_{1,84} =$	4.930
	$p = 0.011$	GBW>REF	$p = 0.021$	GBW>REF	$p = 0.015$	GBW>REF	$p = 0.005$	GBW>REF	$p = 0.029$	GBW>REF
Date	$F_{10,84} =$	3.707	$F_{10,84} =$	4.147	$F_{10,84} =$	2.171	$F_{10,84} =$	2.620	$F_{10,84} =$	2.157
	$p < 0.001$	GBW>REF	$p < 0.001$	GBW>REF	$p = 0.027$	GBW>REF	$p = 0.008$	GBW>REF	$p = 0.028$	GBW>REF
Site*Date	$F_{10,84} =$	2.744	$F_{10,84} =$	2.667	$F_{10,84} =$	1.598	$F_{10,84} =$	2.328	$F_{10,84} =$	1.512
	$p = 0.006$	GBW>REF	$p = 0.007$	GBW>REF	$p = 0.121$	Not Significant	$p = 0.018$	GBW>REF	$p = 0.149$	Not Significant

3.3.1.3 *Rock collections;* Echinogammarus ischnus *and chironomid (midge) larvae*

Results of the ANOVA and post-hoc Tukey tests run on both *E. ischnus* and chironomid larvae indicated that rocks collected in September 2015 contained significantly more *E. ischnus* than those collected in either July or October 2016 (ANOVA chironomid $F_{2,32} = 10.215$, $p < .001$). Few to no chironomid larvae were found from rock collections made in 2016. The increase in *E. ischnus* numbers during summer 2016 is probably due to reproduction (ANOVA *E. ischnus* $F_{2,32} = 33.7$; $p < .001$) (table 2).

Table 2. Whole rock collections mean invertebrate ± standard deviation.

Date	Rocks Sampled	*E. ischnus*	Chironomidae Larvae
9/24/2015	12	203.6±36.4	4.67±1.85
7/1/2016	12	18.1±4.7	0.08±0.08
10/4/2016	11	46.5±6.4	0±0

3.3.1.4 *Chironomid (midge) emergence traps*

Midge trap effectiveness was suboptimal for a number of reasons. Quite often, traps were swamped by the wake of large powerboats leaving the nearby marina, and other times gulls and ducks used them to roost overnight, swamping the trap and causing a loss of data. Traps that fished effectively were analyzed for the difference in midge abundance at all three locations. Midge emergence on both armor stone and GBW were significantly higher than the unaltered control site ($p = .02$ and $p = .001$ respectively). More midges were observed in GBW traps (1.9 midges/trap) than REF (1.6 midges/trap); on average, these differences were not statistically significant. For REF, the off wall site averaged only 0.6 midges/trap in 2015.

3.3.2 Fish sampling and food habits

3.3.2.1 *Overview of collections and diets*

Combined gill netting efforts in 2015 and 2016 resulted in similar species composition with 20 species at the GBW and 13 at the REF (table 3), 9 of which were known only from a single collection. Alewife and round goby were the most common (52% and 29% of catch respectively at GBW, 63% and 24% at REF).

Table 3. Total experimental gill net (EGN) catches from 2015 and 2016 at the GBW and REF.

Species	GBW			REF	
	2015 EGN	2016 Micromesh		2015 EGN	2016 Micromesh
Alewife	540	919		620	1138
Round goby	384	429		278	385
Rainbow smelt	6	328		6	150
Yellow perch	2	77		6	88
White sucker	37	1		48	1
Rock Bass	46	2		24	7
Gizzard shad	18	0		12	0
Largemouth bass	2	13		3	2
Brown trout	6	0		9	0
Walleye	2	0		4	0
Rainbow trout	2	0		3	1
Lake trout	2	0		0	0
Green sunfish	1	1		0	0
Bluegill	1	0		0	0
Common carp	1	0		0	0
Golden shiner	1	0		0	0
Shorthead redhorse	1	0		0	0
Chinook salmon	0	0		0	1
Spottail shiner	0	0		0	1
Nine-spine stickleback	0	1		0	0
Sheepshead	0	1		0	0

An overview of fish diets is shown in Table 4 and Table 5. The more abundant fish underwent further diet analyses (for example, alewife, rainbow smelt, round goby, and rock bass).

Table 4. REF stomach contents from subsample of fish caught during gill netting during 2015 and 2016. Prey items are measured in frequency of occurrence (%Fi) in fish without empty stomachs, and numerical proportion (P_i) of an item in the diet. Other taxa consumed at the REF included Hydropsychidae, Hydracarinidae, Harpacticoida, Isopoda, and terrestrial insects.

	Juv Alewife		Adult Alewife		Round Goby		Rainbow Smelt		Yellow Perch		Rock Bass		Largemouth Bass	
Prey Item	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P
MYSIDACEA														
H. anomala Adult	42	0.12	55	0.42	1	<0.01	88	0.41	60	0.23	43	0.85	100	0.85
H. anomala Juv	7	<0.01	16	0.02	0	0	26	0.05	47	0.21	5	0.02	20	0.13
CHIRONIMIDAE														
Chironomidae larvae	21	0.07	3	0.02	4	<0.01	0	0	6	0.01	0	0	0	0
Chironomidae pupae	51	0.06	38	0.03	16	0.04	14	0.02	17	0.01	19	0.02	20	0.02
CLADOCERA														
Bythotrephes longaminus	4	<0.01	10	0.02	2	<0.01	7	0.01	0	0	0	0	0	0
Bosmina longirostris	7	0.12	3	0.15	0	0	2	<0.01	0	0	0	0	0	0
Chydoridae	0	0	0	0	31	0.71	4	0.11	0	0	0	0	0	0
COPEPODA														
Calanoida	16	0.41	4	0.11	0	0	9	0.26	17	0.54	0	0	0	0
Unidentified zooplankton	14	0.21	19	0.22	0	0	7	0.14	0	0	0	0	0	0

Table 4. Continued.

AMPHIPODA														
E.ischnus	9	0.01	6	<0.01	11	0.01	7	<0.01	0	0	0	0	0	0
Gammarus spp.	0	0	0	0	2	<0.01	2	<0.01	0	0	0	0	0	0
DECAPODA														
Orconectes rusticus	0	0	0	0	1	<0.01	0	0	0	0	5	<0.01	0	0
DREISSENIDAE														
Dreissena spp.	0	0	0	0	79	0.22	0	0	0	0	0	0	0	0
Veliger	2	<0.01	1	0.01	0	0	2	<0.01	0	0	0	0	0	0
FISH														
Neogobius melanostomus	0	0	1	<0.01	0	0	4	<0.01	17	<0.01	43	0.02	0	0
OTHER	0	0	0	0	15	0.02	2	<0.01	0	0	14	0.09	0	0
Number of fish examined	73		122		158		68		61		27		5	
Percent empty	22		21		25		16		13		22		0	
Mean TL(SD) in mm	78(8)		137(23)		73(18)		128(22)		95(42)		167(30)		52(8)	

Table 5. GBW stomach contents from subsamples of fish caught during gill netting in 2015 and 2016. Prey items are measured in frequency of occurrence (%Fi) in fish without empty stomachs, and numerical proportion (Pi) of an item in the diet. Other taxa consumed at the GBW included Alewife, Hydropsychidae, Hydracarinidae, Harpacticoida, Isopoda, and diatoms.

	Juv Alewife		Adult Alewife		Round Goby		Rainbow Smelt		Yellow Perch		Rock Bass		Largemouth Bass	
Prey Item	%F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i	% F_i	P_i
MYSIDACEA														
H. anomala Adult	37	0.07	71	0.53	6	0.01	88	0.54	53	0.10	59	0.97	44	0.09
H. anomala Juv	14	0.02	17	0.02	0	0	37	0.23	38	0.23	0	0	56	0.89
CHIRONIMIDAE														
Chironomidae larvae	22	0.03	13	0.04	21	0.07	2	<0.01	8	<0.01	4	<0.01	0	0
Chironomidae pupae	57	0.03	35	0.02	9	0.01	7	<0.01	18	<0.01	19	0.01	0	0
CLADOCERA														
B. longanimus	3	<0.01	6	<0.01	0	0	1	<0.01	3	<0.01	0	0	0	0
B. longirostris	6	0.08	7	0.13	0	0	1	0.01	0	0	0	0	0	0
Chydoridae	6	<0.01	1	<0.01	21	0.60	5	0.05	0	0.00	0	0	0	0
COPEPODA														
Calanoida	23	0.52	2	0.02	0	0	2	0.05	23	0.66	0	0	0	0
Unident. Zooplankton	18	0.22	10	0.23	0	0	7	0.11	0	0	0	0	0	0
AMPHIPODA														
E.ischnus	3	<0.01	3	<0.01	10	0.02	1	<0.01	0	0	0	0	0	0

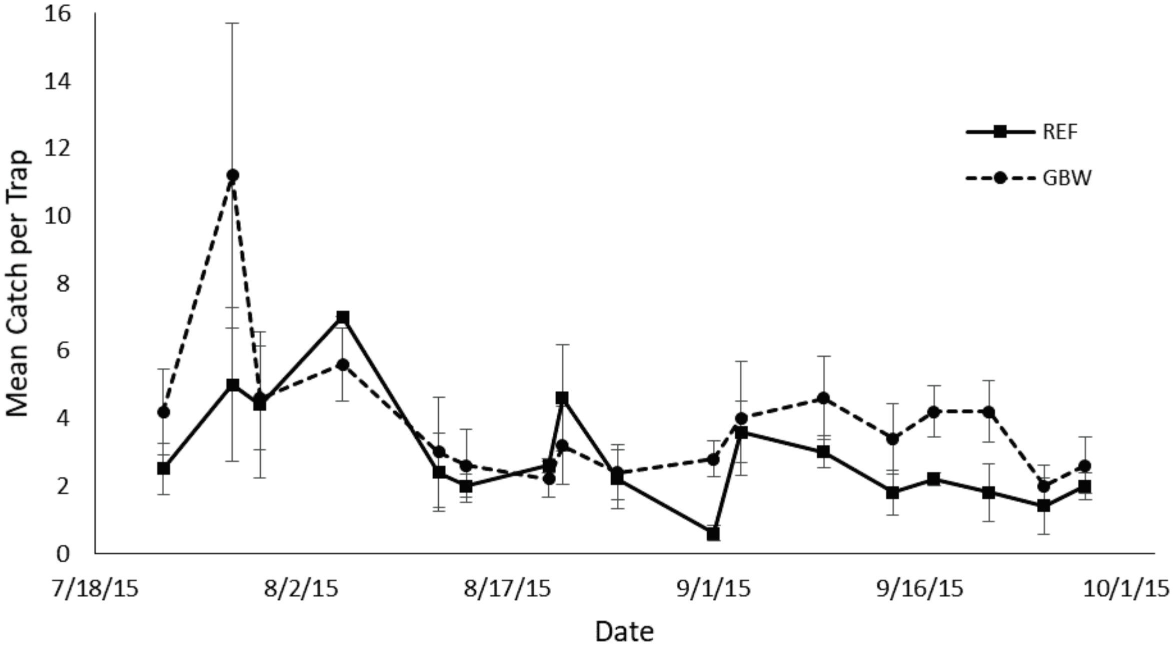
Table 5. Continued.

Gammarus spp.	4	<0.01	0	0	1	<0.01	0	0	0	0	0	0	0	0
DECAPODA														
Orconectes rusticus	0	0	0	0	1	<0.01	0	0	0	0	15	<0.01	0	0
DREISSENIDAE														
Dreissena spp.	0	0	0	0	70	0.26	0	0	0	0	0	0	0	0
Veliger	9	0.02	1	<0.01	0	0	0	0	3	<0.01	0	0	0	0
FISH														
Neogobius melanostomus	3	<0.01	0	0	0	0	0	0	18	<0.01	37	0.02	22	0.02
OTHER	0	0	1	<0.01	11	0.02	1	<0.01	0	0	0	0	0	0
Number of stomachs	98		154		181		98		52		46		13	
Percent empty	19		22		30		17		23		41		31	
Mean length (SD)	76(9)		136(22)		73(26)		127(23)		81(29)		159(21)		74(22)	

3.3.2.2 *Round goby (*Neogobius melanostomus*)*

Round goby catch in minnow traps in 2015 was highly variable at both sites (figure 10). The two-factor ANOVA run on minnow trap catches had no significant site and date interaction ($F_{16,132} = 0.69$, $p = .8$). Both of the main effects were significant (site: $F_{1,132} = 4.55$, $p = .035$; date: $F_{16,132} = 2.18$, $p = .008$). The data suggest that a bias towards the GBW was later in the season; if there is a seasonal change, it could be related to nesting earlier in the season. The round gobies nest in cavities in rocks, and so the GBW may provide these more suitable cavities. Non-nesting round gobies frequently raid conspecific nests for eggs; therefore, they could be attracted to the REF indirectly.

Figure 10. Mean round goby catch from baited minnow traps set in 2015 with standard error bars.



Micromesh gill net catches from 2016 were also variable with slightly more round gobies present at the GBW (table 3). The two-factor ANOVA run on gill-net catches had no significant effects for site ($F_{1,13} = 1.15$, $p = .303$) or date ($F_{13,13} = 2.06$, $p = .102$). Therefore, this sampling showed no evidence that round gobies preferred the GBW's smaller stone, but the micromesh gill nets collected mainly round gobies smaller than reproductive size.

Round goby diets, summarized in table 4 and table 5, were typical of those reported elsewhere (reviewed in Kornis, Mercado-Silva, and Vander Zanden 2012), with smaller individuals feeding mainly on aquatic arthropods and larger individuals feeding on dreissenids.

3.3.2.3 *Alewife (*Alosa pseudoharengus*)*

Alewife was the only species present in all gill net sets as well as the most abundant species at both sites (table 3) with a wide size range that included both yearlings and mature individuals (figure 11). Overall, more alewives were netted at the REF than at the GBW (table 3). The two-factor ANOVA run on gill-net catches had no significant effects for site ($F_{1,13}$ = 0.039, p = .846) or date ($F_{13,13}$ = 1.26, p = .343) (figure 12).

Figure 11. Alewife total length (TL) histogram from fish with stomachs sampled in 2016 indicating a year class of age <1 alewife between 70 mm and 90 mm TL.

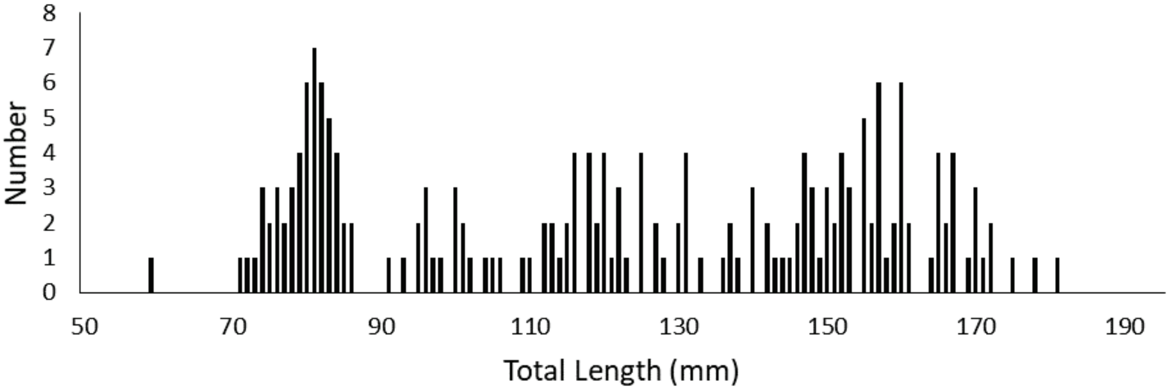
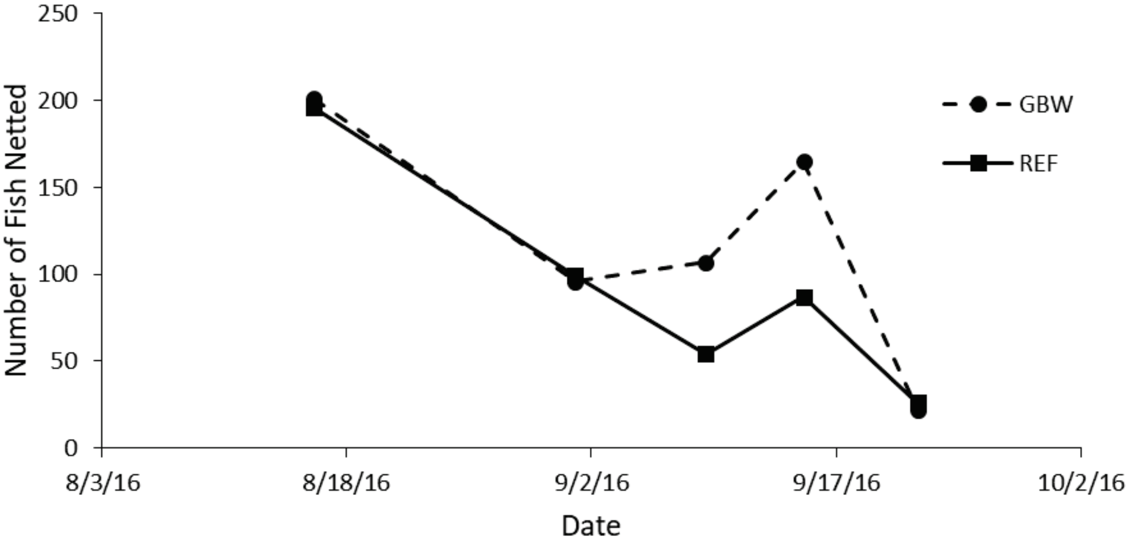


Figure 12. Number of alewife collected in gill nets in 2016 by site and date. There were no detectable statistical trends.



Alewife fed heavily on *H. anomala* at both the GBW and REF, and *H. anomala* was numerically the most abundant food item consumed at both sites. Both the frequency of occurrence and proportion of *H. anomala* in adult alewife stomachs were greater on the GBW than at the REF (table 4 and table 5). However, the two-factor ANOVA analyzing *H. anomala* consumption by alewives had no statistically detectable site effect ($F_{1,107}$ = 0.072, p = .789) and the site and date interaction was also suggestive ($F_{9,107}$ = 1.747, p = .087. There was a significant date effect ($F_{9,107}$ = 3.62, p = .001). Chironomids were expected to be quite important to adult alewife because of the results reported in Kornis and Janssen (2011) but made up only a small share of the diet at both sites (GBW: P_i = 0.06, Reference: P_i = 0.05).

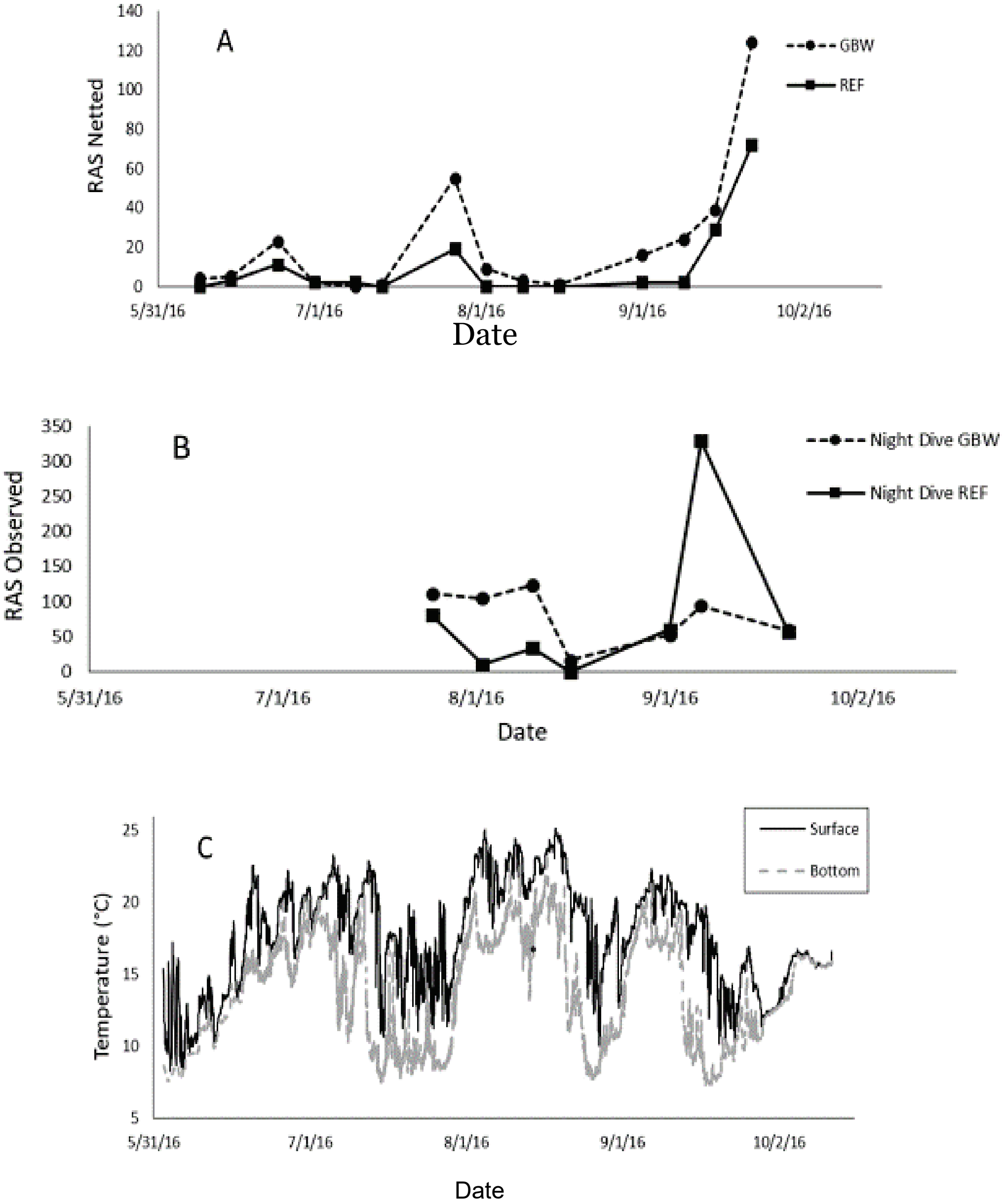
Differences in stomach content composition of juvenile and adult alewife were numerically assessed. Juvenile alewife foraged more often on zooplankton and chironomids than larger adults did (table 4 and table 5).

3.3.2.4 *Rainbow smelt (*Osmerus mordax*)*

Rainbow smelt were the third most abundant species in 2016 at both sites (after very few were caught in 2015) (table 3). Over twice as many rainbow smelt were netted at the GBW than at the REF in 2016. The two-factor ANOVA on gill-net catches showed significant effects for both site ($F_{1,13}$ =

13.65, $p = .003$) and date ($F_{13,13} = 9.087$, $p < .001$). Catch was highly variable but increased in relation to prolonged upwelling events when cool water was present at the GBW for several consecutive days (figure 13).

Figure 13. Rainbow smelt (RAS) catch in gill nets (A) and night dive (B) observations from 2016 sampling plotted against surface (2 m) and bottom (7 m) temperature (C) at the GBW during 2016 sampling.



In the three-factor ANOVA for night dive observations, because the highest order interaction (site and date and depth) is statistically significant, the statistically significant main effects and lower order interactions are difficult to interpret (Zar 1999; statistical analysis contained in table 6).

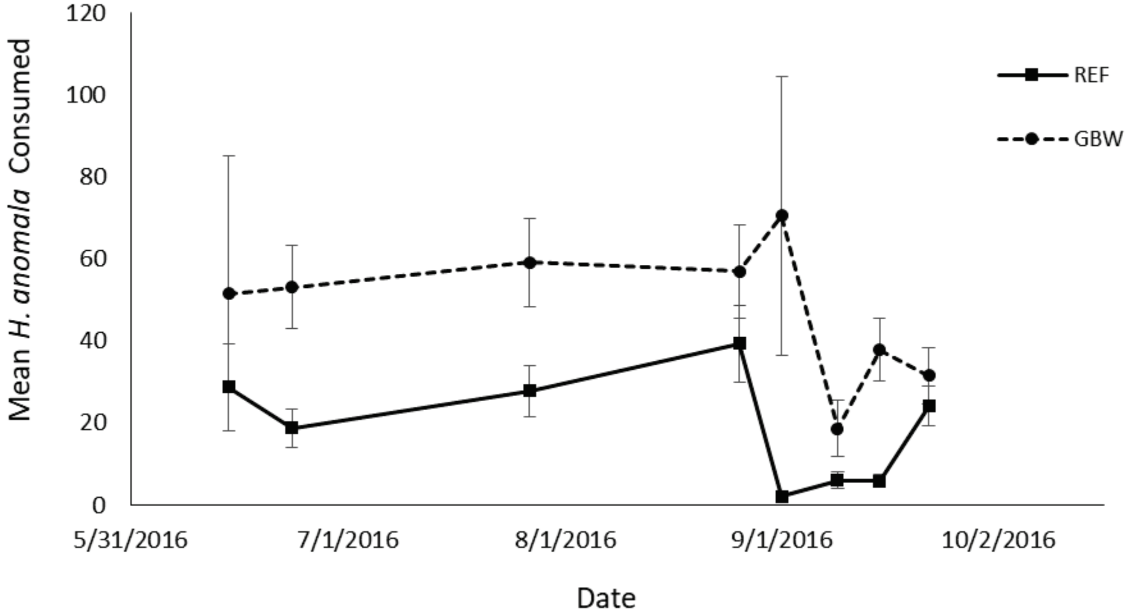
The night dives indicated a complex interaction between site, depth, and date that is most likely related to cold water upwellings, with more rainbow smelt observed when there was cold water present.

Table 6. Three-factor ANOVA of number of rainbow smelt seen at deep versus shallow transects at the GBW versus the REF.

Source	Degrees of Freedom (df)	F	*p*
Site	1, 112	4.99	0.027
Date	6, 112	8.58	<0.001
Depth	1, 112	281.46	<0.001
Site*Date	6, 112	6.93	<0.001
Site*Depth	1, 112	14.79	<0.001
Date*Depth	6, 112	7.44	<0.001
Site*Date*Depth	6, 112	9.73	<0.001

Rainbow smelt fed primarily on *H. anomala* at both sites throughout the sampling period ($P_i = 0.77$ at GBW and $P_i = 0.46$ at REF; figure 14). Rainbow smelt at the REF tended to consume more zooplankton than they did at the GBW (REF: $P_i = 0.52$, GBW: $P_i = 0.22$). The two-factor ANOVA analyzing rainbow smelt consumption of *H. anomala* did not have a significant site and date interaction ($F_{6,78} = 0.934$, $p = .47$). Both the main effects were significant with the Site effect ($F_{1,78} = 7.38$, $p = .008$) indicating greater numbers of *H. anomala* for rainbow smelt capture at the GBW versus the REF. This pattern of greater *H. anomala* abundance in smelt stomachs complements sampling results from *H. anomala* traps which also indicated that *H. anomala* were significantly more abundant at the GBW than at the REF. The date effect was also highly significant ($F_{1,78} = 3.57$, $p = .004$), probably due to lake upwelling and downwelling effects allowing or restricting rainbow smelt access to the breakwater.

Figure 14. Mean number of *H. anomala* found in the stomachs of rainbow smelt in 2016 with standard error bars.



3.3.2.5 *Rock bass (*Ambloplites rupestris*)*

Rock bass were collected almost exclusively in experimental gill nets in 2015. This effort was abandoned for EGNs in 2016 due to concerns that rock bass, likely being residential, might have decreased in abundance due to sampling. Rock bass caught at the GBW were generally smaller than those on the REF (mean TL 159 mm and 167 mm respectively, table 4 and table 5) although a paired *t*-test indicated they were not significantly different ($t_{60} = 1.3$, $p = .09$). The smaller rock bass were frequently observed at the GBW during night dives, although quantitative length data was impossible to obtain during such sampling.

The night diving observations indicated that, at least when the shallow water was warm, rock bass were preferentially at the GBW versus the REF (figure 15). The ANOVA (table 7) was complex, with a highly significant site and depth and date interaction (table 7). However, treating the shallow data as an Analysis of Covariance (ANCOVA) with temperature as a covariate and site as a group variable produced a significant site and temperature interaction (figure 15; $F_{1,10} = 5.28$, $p = 0.044$) indicating nonparallel slopes for GBW versus REF (for site, the group variable, $F_{1,10} = 3.41$, $p = 0.095$ and for temperature, the covariate, $F_{1,10} = 24.1$, $p = 0.001$). This result suggests that, during a cold-water upwelling, there was no difference in rock bass seen, but more were seen at the GBW when the water was warm. In cold water the rock bass were lethargic, and we suspect many may have been hiding in the rock cavities, and so out of view of the divers.

Figure 15. Rock bass seen in the shallower half of the GBW during night dives in relation to shallow temperature. Note that there is a trend towards more rock bass with warmer water and that there tended to be more rock bass seen on the GBW compared to the REF.

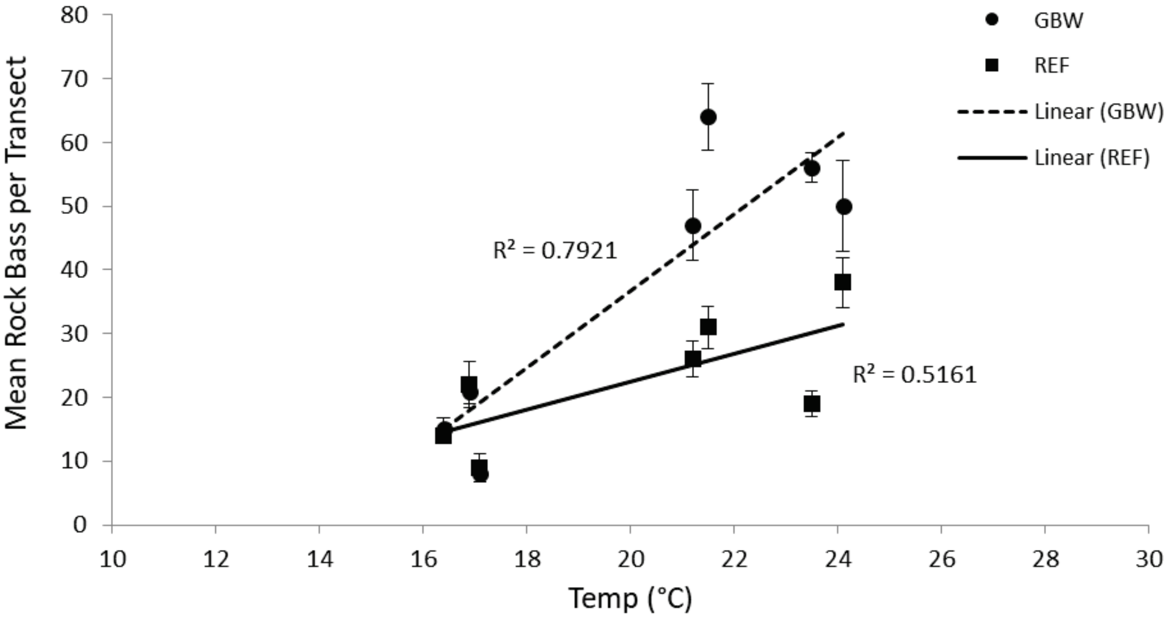


Table 7. Three-factor ANOVA analyzing the log(n+1) transformed number of rock bass observed on night dives in 2016. N.S. = Not Significant.

	df	F	*p*	Effect
Site	1, 112	1.47	0.228	N.S.
Date	6, 112	14.3	0.001	GBW>REF
Depth	1, 112	68.11	0.001	Deep>Shallow
Site*Date	6, 112	2.17	0.051	N.S.
Site*Depth	1, 112	8.19	0.005	GBW>REF
Date*Depth	6, 112	5.93	0.001	Deep>Shallow
Site*Date*Depth	6, 112	3.33	0.005	GBW>REF

Rock bass consumed primarily *H. anomala* at both sites throughout the study (REF: P_i =0.87, GBW: P_i =0.97). The two factor ANOVA had no significant effects for either date ($F_{9,14} = 1.52$, $p = .233$) or site ($F_{1,14} = 0.282$, $p = .604$). Because sample size was small for many dates, the significance of site and date interactions could not be determined.

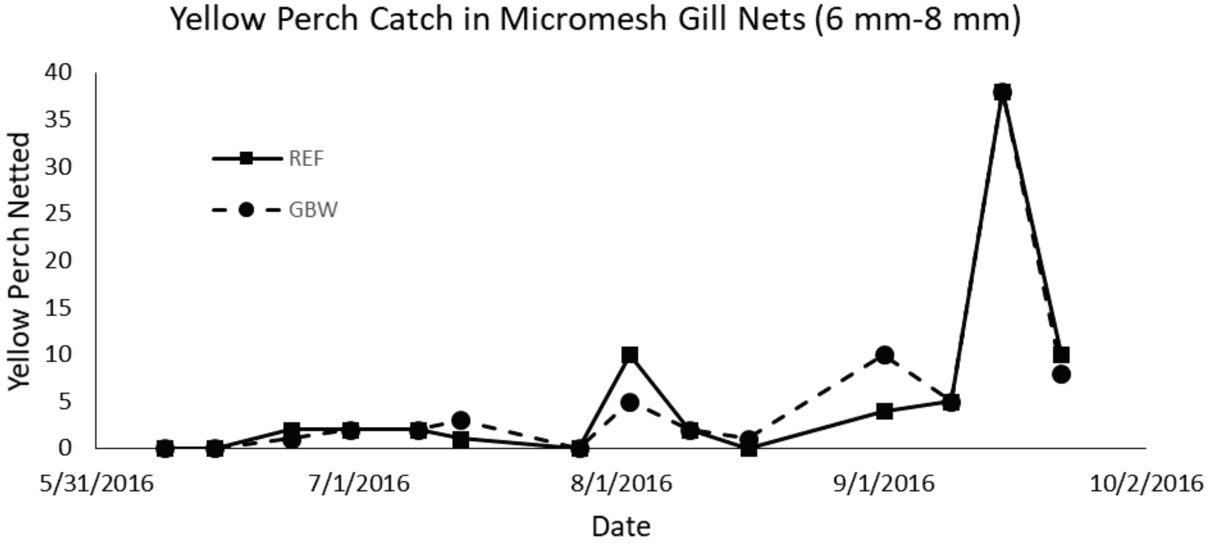
From 2015-collected rock bass at the GBW, round gobies were the second most commonly consumed item (Fi = 37%) followed by chironomid pupae (Fi = 19%), and rusty crayfish (Fi = 15%). Larger prey items such as round gobies and crayfish were often coconsumed with *H. anomala*, and although larger fish tended to consume round gobies, no clear shift to piscivory was observed.

3.3.3 Irregular but important management species

3.3.3.1 *Yellow perch (*Perca flavescens*)*

A majority of the yellow perch gillnetted were young of year (YOY) which had probably recently returned to shore, after the larvae have drifted in lake currents from where they hatched (Dettmers et al. 2005; Beletsky et al. 2007) (figure 16). There may also be a distinct harbor population of perch, which could be the subject of future analysis. As pelagic larvae in Lake Michigan, YOY yellow perch feed primarily on zooplankton, making the shift to benthic invertebrates after they return to nearshore habitats. Many of these YOY yellow perch may have been too small to forage on the elusive adult *H. anomala* but were able to consume juvenile *H. anomala,* which are typically 1–2 mm in length, similar in size to the mobile calanoid copepods which yellow perch fed heavily on at both sites (REF: P_i =0.54, GBW: P_i =0.66). A few YOY yellow perch gorged on juvenile *H. anomala*, with one individual caught on the GBW consuming 291 juvenile *H. anomala* and accounting for 52% of all juvenile *H. anomala* consumed by yellow perch at the GBW. The same was true at the REF, where four of the yellow perch sampled contained 53% of all juvenile *H. anomala* consumed there.

Figure 16. Gill net catch of yellow perch during summer 2016.



Yellow perch catch were almost entirely from micromesh nets set in early September 2016, when YOY perch begin settling back to shore after drifting pelagically as fry (Dettmers et al. 2005; Beletsky et al. 2007). The two-factor ANOVA run on gill-net catches had no significant effects for site: ($F_{1,13}$ = 0.708, p = .415), but did indicate a significant effect for date: ($F_{13,13}$ = 13.22, p < .001) that probably reflected settling events.

3.3.3.2 *Largemouth Bass (*Micropterus salmoides*)*

Few largemouth bass were sampled at either site during the study (REF: N = 5, GBW: N = 13). Those caught fed almost exclusively on *H. anomala* (P_i =0.98 for both sites).

4 Spawning Assessments

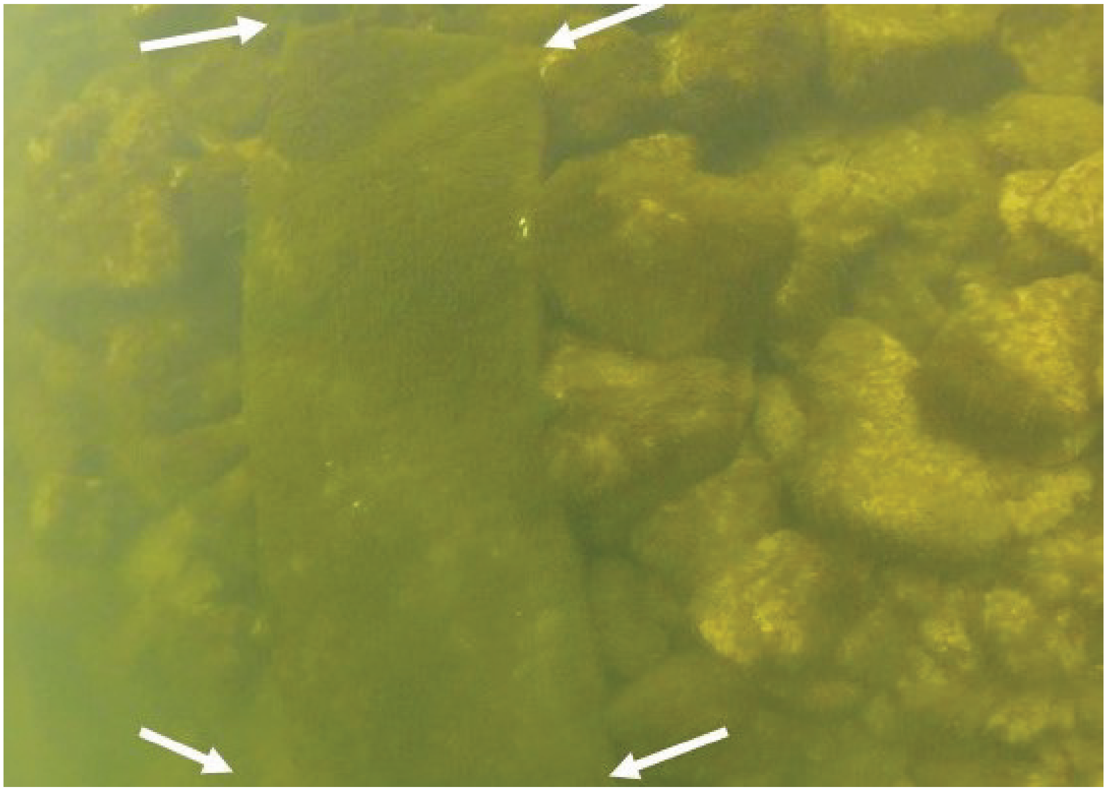
4.1 Spawning results and discussion

4.1.1 Broadcast spawners

Broadcast spawning refers to spawning by non-nesting or brooding fishes. In general, during broadcast spawning a female is surrounded by several males, and the ensemble releases their gametes at the same time. There is no nest, but the location for gamete release spawning is neither random nor highly targeted. The likely broadcast spawners at the GBW were two summer spawners, alewife and spottail shiner (*Notropis hudsonius*), and the autumn-spawning lake trout (*Salvelinus namaycush*). The former two species commonly deposit sticky eggs along breakwaters and similar natural structures. These are easily seen, because the eggs adhere to rocks or the algae on the rocks. Lake trout deposit their eggs in the crevices of loose cobble, where they incubate over winter and hatch in spring.

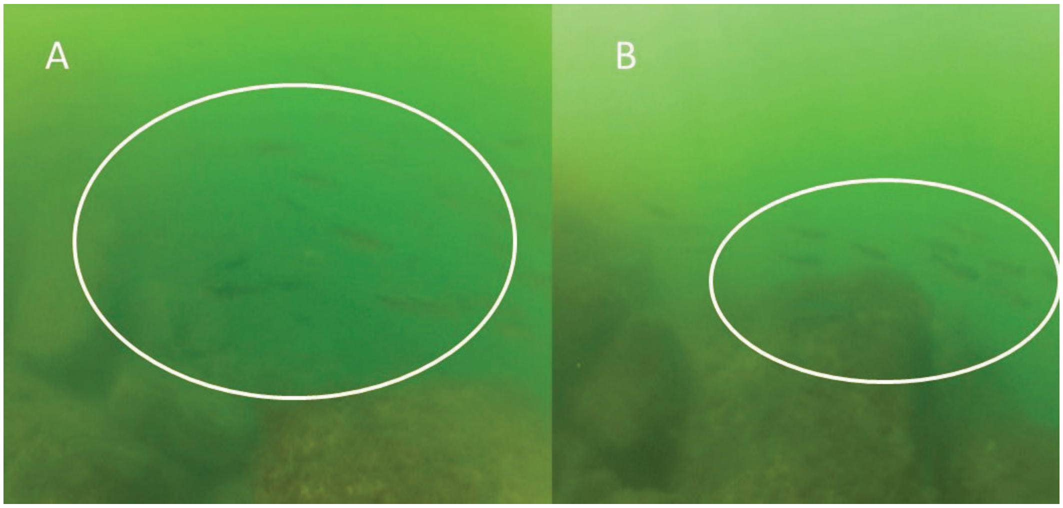
For spring broadcast spawners, ten artificial turf carpets were deployed from April through July 2015, with five at the GBW and five at the REF (figure 17). They failed to collect any eggs and several were lost due to sliding downslope (probably as part of rockslides). They were found at the base of the GBW sections during later dives. Others were somewhat disturbed or flipped by tangled sport fishing gear.

Figure 17. Carpet deployed to collect eggs from broadcast spawning fishes. Arrows mark the edges of the carpet.



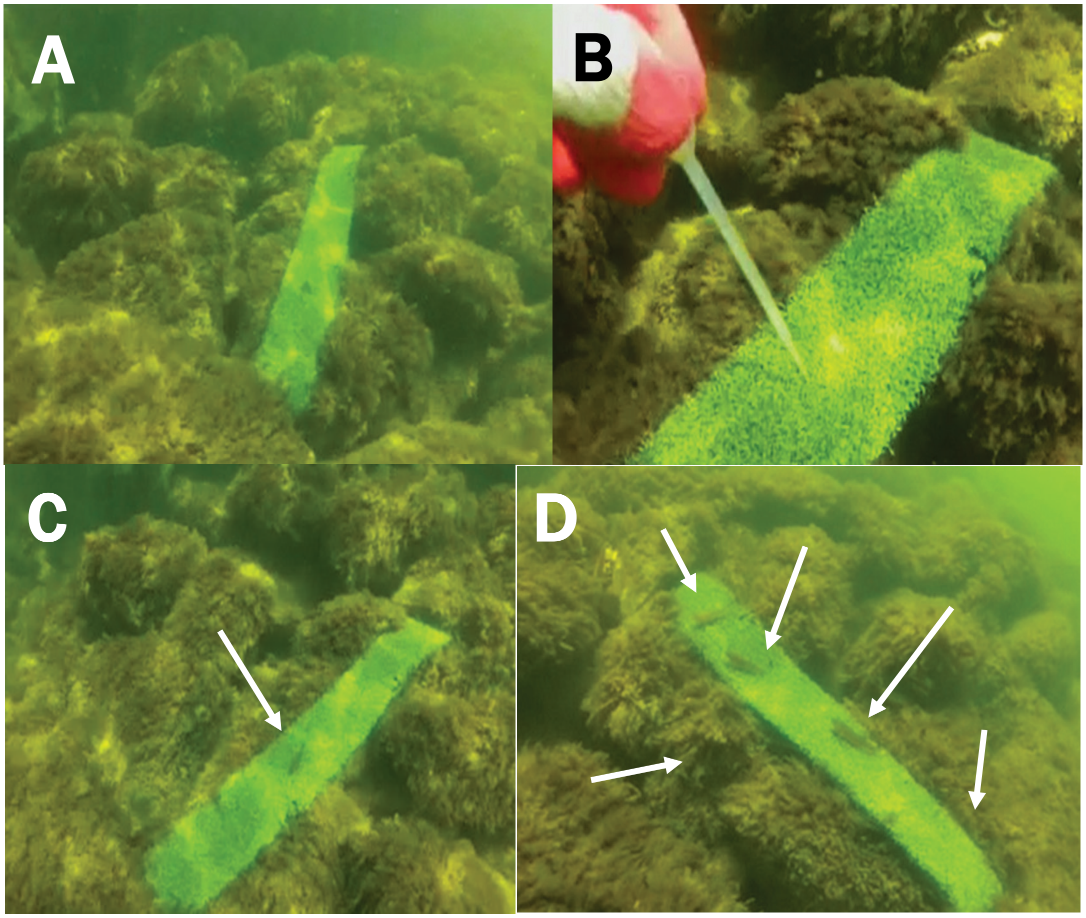
Carpets were routinely checked for eggs during snorkeling and dives. During the first three weeks the carpets were deployed, there was scarce evidence of alewife activity and no spottail shiners (which were only rarely captured during the study). During the week of 19–25 July 2015, mature alewives were finally present in spawning aggregations, and egg deposition was observed on the GBW during a snorkel on 21 July (figure 18). However, upon retrieval and washing of the egg mats, no alewife eggs were discovered. Round goby densities are so high along the breakwater that it may be that many of the eggs deposited on the open surface of the egg mats are subject to goby predation.

Figure 18. Alewife spawning aggregations on the GBW.



To test this hypothesis, on 23 July 2015 eggs were stripped from a mature female alewife and fertilized by a male that was stripped of sperm. The fertilized eggs were deposited onto a small test piece of the carpet (figure 19). Shortly after the eggs were deposited on the carpet, many round gobies emerged from the nearby rocks and began picking the eggs off the egg mat and surrounding rocks where some eggs ended up. No research on goby predation on alewife eggs currently exists, and this predation may be yet another contributing factor to declining alewife recruitment in Lake Michigan.

Figure 19. Photos from an alewife egg predation test taken in chronological order from A–D over several minutes: (A) the test strip of egg mat anchored to the bottom; (B) alewife eggs are applied to the egg mat; (C) one goby eating eggs off the egg mat almost immediately; and (D) three gobies eating eggs off of the mat, with several others eating eggs that spilled onto adjacent rocks minutes after eggs were deposited.



Because fish eggs are large enough to be seen by divers, and because frequent diving operations were conducted, diving observations for examination of broadcast spawning were relied upon. It is thought that fishes that deposit eggs on rock surfaces likely lose nearly all their eggs to round goby predation.

4.1.2 Alewife, further details and notes

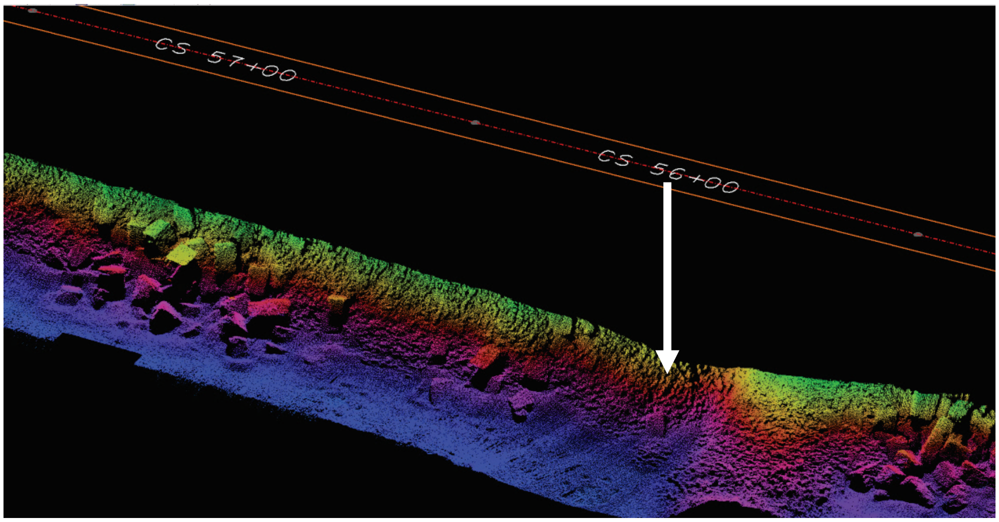
Of the summer-spawning fish species in the harbor, alewives are of particular interest, because lake-wide alewife numbers are below levels necessary for maintaining the sport salmon fishery. Reliable information about the spawning activity and recruitment of this year class of alewife; therefore, it is vital to future management actions. In 2015 the EGN set during the spawn yielded more alewives from the GBW than the adjacent REF. Typically male alewife were more abundant than females on spawning grounds, and all males were ripe and running milt. The prolonged 2015 upwelling event likely affected alewife spawning in that activity continued much later into August than typically would occur. As late as 9 September 2015, female alewife were still observed ripe with eggs, indicating that the prolonged upwelling may have delayed or inhibited spawning by some individuals altogether. During mid-July of 2016, the team stopped setting gill nets for two weeks and began snorkel surveys, as ripe adult alewife began showing up in nets. Again, the team did not observe any alewife eggs adhered to either rocks or periphytic algae at the GBW or REF during any snorkel or dive survey. Divers did observe some young of year (YOY) alewives during snorkel surveys in September of 2015 and 2016 when YOY began schooling together. Numerous schools of YOY alewife were also observed at the boat landing in the nearby McKinley Marina on 24 August 2016, indicating that at least some alewife production occurred locally in 2016. The micromesh gill nets were also successful at sampling YOY alewife in both years as they reached >60 mm in length.

4.2 Lake trout (*Salvelinus namaycush*)

Egg traps were set at each end of the GBW (figure 20), where it was expected that lake trout spawning was most likely to occur based on previous research (Marsden et al. 2016). Riley et al. (2019) found that eggs were typically deposited near the summit of a slope that intercepted a current. At the GBW and REF, the team found that the current parallels the long axis of the breakwater and usually moves south to north. Consequently, egg trap deployment in 2015 and 2016 focused on the GBW summit and at its north and south ends. Traps were placed between 1 m and 2 m deep, close to the exposed armor stone and along the ridge tapering down the slope.

Substrate surface lake trout egg traps (Riley et al. 2010) were deployed on the GBW from 14 October 2015 to 16 November 2015, and 22 buried egg traps were set from 24 September 2016 to 10 November 2016. Buried egg traps are tedious to deploy and recover but less susceptible to being dislodged, which was a problem with the 2015 traps. No eggs were found deposited in any of the egg traps in either year.

Figure 20. The very south end of the GBW appears to have the best substrate for lake trout spawning, just south (right) of 56+00. Present there is a summit of a slope of cobble that intercepts a current.



A gravid female lake trout was taken with the last gill net setting of 2016 at the end of September and about two weeks before expected spawning to start. The team did not want to disturb any lake trout trying to spawn; therefore, all overnight gill netting was ceased. During the 2016 egg trap deployment, one short (1 h) gill net set perpendicular to the GBW was laid on 10 November 2016 hoping to capture staging fish.

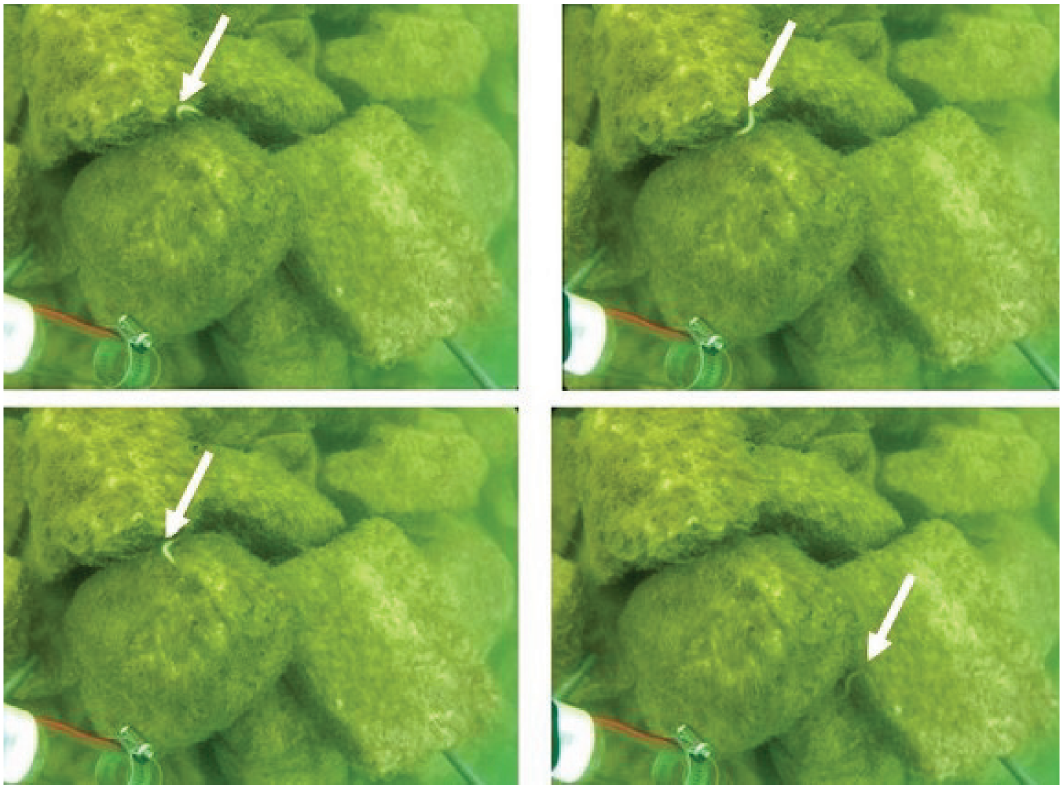
It is thought that lake trout eggs can survive to hatching at the GBW. In late October 2014, arrangements were made for WDNR to collect and fertilize lake trout eggs which were subsequently placed in egg incubators by the team (figure 21). The three deepest incubators were filled with mud, but the shallowest (about 2 m deep) had 20% survival with mostly clean egg cells. This is comparable to other investigations and, in the lab, there is generally about 50% survival to hatching and 25% to free swimming. The incubators were important for three reasons: first, evidence was present that lake trout could reproduce at the GBW; second, this allowed the team to estimate when electroshock should be performed for lake trout fry; and third, it was indicated that egg suffocation due to sedimentation was a potential issue for eggs deposited at deeper portions of the GBW, which focused our egg trapping efforts along the shallower summit of the reef in 2015 and 2016.

Figure 21. Lake trout fry from an egg incubator that overwintered at the GBW.

Eggs were fertilized 23 October 2014, incubators deployed 30 October, 2014, and the incubators recovered 6 April 2015. Survival to fry stage was about 20%, similar to that in other studies using such incubators. There were 10 fry, with 2 damaged while opening the incubator. Healthy ones filled swim bladder by 7 April, except the one with the most yolk.

Electroshocking produced one fish that we are rather certain is a lake trout fry based on its size, body shape, and swimming (figure 22). The team attempted electroshocking at several sites during both years; the one with the putative fry was at the very south end of the GBW. Of the sampled sites, this sector appears to have the best substrate.

Figure 22. Arrows mark putative lake trout fry captured from video taken via a remote operated vehicle (ROV). Four frames from video.



Video was also captured on 3 November 2016 using a remote-operated vehicle (ROV) set on the bottom and experimental deployment of a stationary camera (GoPro Hero2 on a tripod) to passively assess the presence of lake trout spawning aggregations on the GBW near where traps were set. Several gizzard shad and the ghostly outline of a larger fish, possibly a lake trout, were observed, but visibility along the rocks was only a few meters, so the team was unsure of its identity. It is also quite possible that there may have been lake trout staging just off the reef in deeper water, as multiple fish were observed on the sonar while running the ROV. However, visibility away from the breakwater was poor, and no fish were observed near the boat when retrieving the ROV. After reviewing the stationary camera footage, it was also determined that similar deployments may also prove to be a useful method during summer sampling to capture fish on camera that may be shy to a diver and stay just out of sight.

Lack of evidence of lake trout spawning is not surprising, As there have been similar findings for artificial reefs at Thunder Bay, Lake Huron, where established spawning reefs are attracting lake trout, but the artificial reefs also appear to attract lake trout after a few years (Marsden et al.

2016). Olfactory cues from previous spawning apparently draw lake trout to previously used spawning reefs (Foster 1985), so there may be a seasoning effect. Some Lake Superior spawning reefs where the local population was extirpated were restored by depositing fertilized lake trout eggs (Hansen et al. 1995). Nonetheless, the team is fairly certain that one lake trout fry was found in May 2015 at the GBW. After experiences at Yellowstone Lake (2014) and Lake Huron (2015), the team thinks that electroshocking with the ROV for fry is more efficient than egg traps. Using the ROV allows the team to cover more ground efficiently and requires less labor and no dive times to sample.

4.3 Nesting Species

During scuba and snorkeling dives, the team checked for nesting species and in 2016 deployed five nesting shelters to attempt to attract round gobies, rock bass, largemouth bass, or smallmouth bass.

4.3.1 Round goby

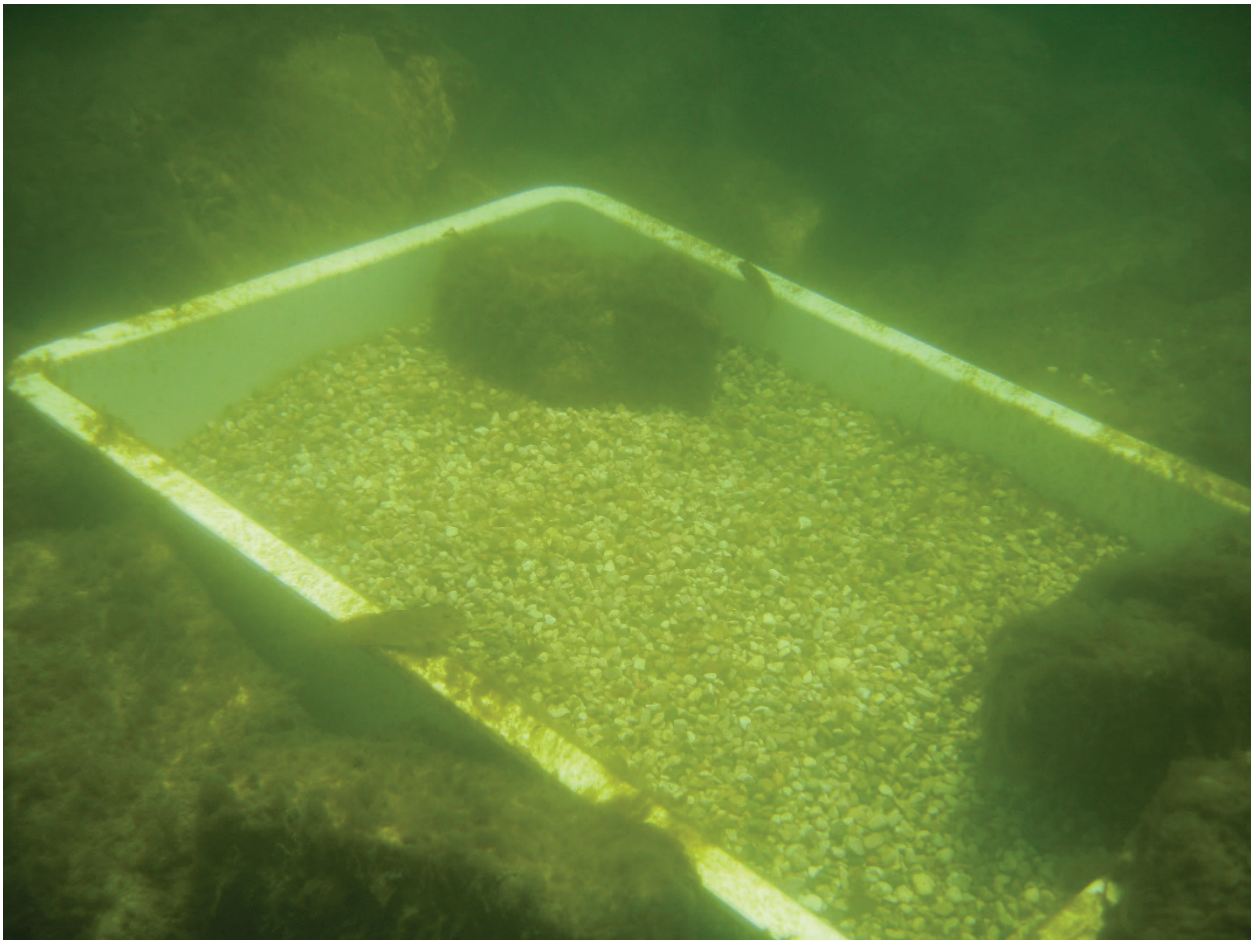
Round gobies are cavity spawners, and nests are very difficult to uncover due to the complexity of the reef rock size and angle of the reef. Several nests were uncovered in June 2015, but the physical excavation of cobble produced limited results for high effort. Many nests may be present deeper within the reef, where suitable caves exist. Nests were observed in dynamite boreholes, which are likely ideal nest sites. An abundance of YOY gobies occupying the base of the GBW during September 2015 dives indicates that there was a successful goby spawn on the reef.

4.3.2 Rock bass

Nesting behavior of the rock bass on the GBW on either the deposited cobble or nest boxes was observed. Exploration of the nearby McKinley Marina, Summerfest Lagoon, and Discovery World Lagoon showed the remnants of many old nests and active nesting sites at all three locations every year from 2016 to 2019. There was also a great abundance of young rock bass about 5–7 cm long, indicating that this is the likely source population for the rock bass seen using the GBW.

In 2016 four gravel-filled nest boxes were deployed at the GBW (figure 23) in early June, prior to when rock bass nests with eggs at Summerfest Lagoon were observed. These boxes never showed any sign of nesting activity, which would have been obvious because the males fan out a depression in the gravel.

Figure 23. Nest box filled with pea gravel deployed at the GBW to attract nesting centrarchids.



4.3.3 Largemouth bass and smallmouth bass

Neither species were seen spawning on the GBW, either on the deposited cobble or the nest boxes. In 2016 males of both species were found guarding fry at Summerfest Lagoon and Discovery World Lagoon. However, many YOY largemouth bass (figure 24) and some adult smallmouth bass occupied the reef throughout the summer. In exploration of nearby spawning habitats, bass of each species were observed guarding fry that had hatched recently in the lagoon at Lakeshore State Park. Again, these young fish dispersed, and at least some largemouth bass YOY have been taking advantage of the rich food resources on the GBW.

Figure 24. YOY largemouth bass seen on the GBW during a visual survey.

5 Discussion

The breakwater at Milwaukee Harbor constitutes a “novel ecosystem” in that it combines a physical structure of natural and nature-based features with a mixture of native and invasive species interacting in the food web (Hobbs, Higgs, and Harris 2009). With regards to the REF, while rocky habitats dominate the western side of Lake Michigan (Janssen, Berg, and Lozano 2005), boulders the size of armor stone are uncommon, and no known examples exist in which such large rocks are piled to 6–7 m high. Glacial deposits known as drumlins can be quite large but have a mixture of stones lacking deep cavities. The piling of armor stone results in extensive large interstitial spaces termed *caves*. The smaller rock covering the armor stone at the GBW creates smaller interstitial spaces that form a veneer over the armor stone and its caves; thus, a different physical habitat results as compared to the armor stone.

The faunal differences between the GBW and REF are likely due to strongly lithophilic species combined with as yet, undocumented differences in preferences or adaptations to different sized rocks. It is not surprising that rock bass were a major component and likely have an ontogenetic shift in preference for larger rocks as they grow. The major forage species, *H. anomala*, has congeners that associate with caves (Rastorgueff et al. 2011). Therefore, the artificial caves in the armor stone may be promoting the local success of *H. anomala* and, subsequently, likely drove the apparent preference for the GBW, which is associated with higher predation rates for *H. anomala*. Alewife showed no apparent habitat preference, perhaps related to being very mobile and pelagic, but the association of *H. anomala* with both the GBW and REF has provided this key forage fish for salmon and trout with a locally abundant, novel prey.

A complicating factor is temperature, due to frequent cold water upwellings. Milwaukee lies in a coastal zone that has the most frequent incidences of upwellings (Mortimer 2004; Plattner et al. 2006). Temperatures recorded show that upwellings penetrate the harbor with apparent impacts on certain fishes. For warmwater species such as rock bass, this might be considered disruptive, but it also provides opportunity for cold water species such as rainbow smelt to access *H. anomala*, a prey closely related to an important deepwater prey, *Mysis diluviana*.

Additionally, Lake Michigan's fauna includes diverse, nonindigenous species. The breakwater habitat includes many nonindigenous species, but these all occur throughout Lake Michigan, so this is not seen as the reason for the breakwater habitat to promote invasions. The views here are pragmatic in the sense that what is valued depends in part on stakeholder perspectives.

Both the GBW and REF provide potential for novel interspecies interactions. The predominant organisms include both native and introduced species, and these may be divided into three categories. Broad range animals include species that are found both along coastal Lake Michigan and in estuaries. Coastal species are found along Lake Michigan's open coast. Estuarine species are found around river mouths but generally are not along the open coast. The GBW and REF are also novel habitats in that they provide a location at which coastal and estuarine species can interact. Because the available species are unlikely to be the same at differing Great Lakes locations, thus producing spatially variable species ensembles, the interactions among species is difficult to predict.

5.1 Groups of species

Before discussing the GBW and REF site ecosystems, the major broad range, open coast, and estuarine groups of species are discussed.

5.1.1 Broad range species

Observations were made of *H. anomala* at natural rocky habitat on the open coast to a depth of about 15 meters and also in the Milwaukee Inner Harbor to at least 1.7 km upstream of the river mouth.

Amphipods are ubiquitous. Species were not specified; however, both native (*Gammarus*) and invasive (*Echinogammarus*) species were at the breakwaters and in fish diets.

Round gobies occur in tributaries, including the Milwaukee River, to at least 100 m deep in Lake Michigan

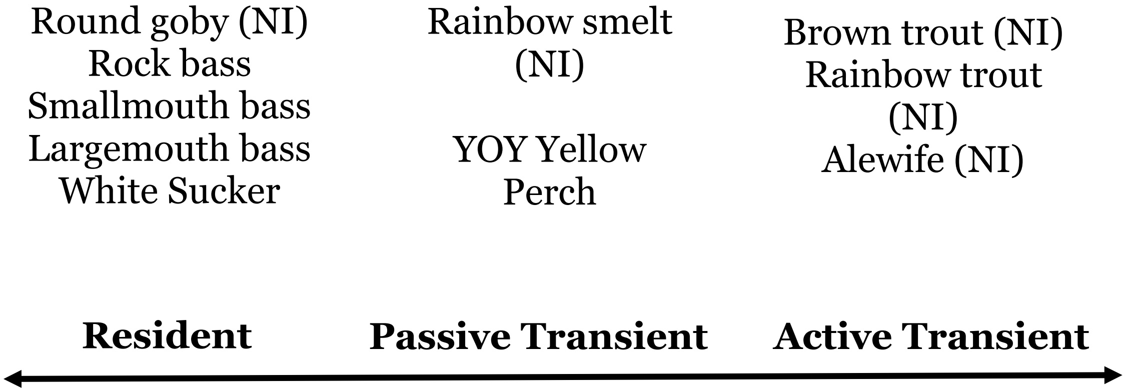
Lake Michigan is the only deep Great Lake (Lake Erie is shallow) that has an open coast yellow perch population. Additionally, there may be a Milwaukee River/Estuary population as well. Juveniles captured were likely spawned along the coast, drifted until about 50 mm total length, then some settled from their pelagic drift at the breakwater (Dettmers et al. 2005).

Alewife and rainbow smelt are both nonindigenous species and have been major forage species for diverse fishes, including the nonindigenous Pacific salmons. They tend to be found offshore, scattering after the spawn and wintering offshore, and both migrate to the coast in spring to spawn (rainbow smelt in April and alewife May–July).

5.2 Species interactions

Figure 25 shows that novel ecosystem interactions are perhaps best demonstrated by the predator-prey interactions which we have categorized as Indigenous-Indigenous, Indigenous-Nonindigenous, and Nonindigenous-Nonindigenous.

Figure 25. Spectrum of fishes commonly found in the GBW and outer harbor along a continuum of seasonal and conditional occupancy. Resident species are those that occupy the GBW at least from midspring through midautumn. Passive transient species are those in residence likely only under certain hydrodynamic conditions.



Rock bass–crayfish. This is not a perfect indigenous-indigenous interaction because the crayfish at the breakwater, rusty crayfish, is native to Ohio, Indiana, and Kentucky and has locally replaced two native species. The native crayfishes were important in the diets of adult yellow perch in Lake Michigan (Quinn and Janssen 1989) and, in general, crayfishes are important in the diets of both rock bass and smallmouth bass in inland waters (Probst et al. 1984). Hence it is likely that crayfish would be important in the diet of yellow perch and smallmouth bass should they increase their occupation of the breakwater. Night dives indicated that crayfishes were more abundant at the GBW than REF; however, the counts were highly inconsistent.

5.2.1 Indigenous-Nonindigenous

Rock bass–*H. anomala*. Predation by generally smaller rock bass on this invasive mysid is novel. The source of young rock bass is probably inside Milwaukee Harbor or its tributaries. It is likely that certain caridian shrimps of the Palaemonidae occur in rock bass diets; however, there have been no sources to confirm this. Smaller rock bass tended to occupy the GBW, so the generally higher densities of *H. anomala* at the GBW may be a factor.

Rock bass–round goby. Round gobies were the major prey for the larger rock bass. Because larger round gobies feed extensively on dreissenids, this interaction is likely very important to the breakwater ecosystem.

Yellow perch–*H. anomala*. The yellow perch collected were primarily small, and their source was likely not Milwaukee Harbor but elsewhere in Lake Michigan. Yellow perch larvae and fry drift for two months or more after emerging from their demersal eggs that are spawned in late May to early June (Dettmers et al. 2005). At settlement the fry are about 50 mm.

Other. It is suspected that other species, such as juvenile largemouth bass and smallmouth bass are attracted to the GBW and/or REF due to either shelter or abundant prey. These are warm/coolwater species and, at locations without frequent cold-water upwelling, have better connectivity or greater sources of recruitment; these fish could be important components of the breakwater ecosystems. For example, at an artificial reef at the southern end of Lake Michigan near Chicago, smallmouth bass and rock bass are common summer residents (Creque et al. 2006). The region around Milwaukee Harbor has the most frequent cold-water upwellings in Lake Michigan; such upwellings are rare at the southern end of the lake (Plattner et al. 2006).

5.2.2 Nonindigneous-Nonindigenous

Round goby–quagga mussel. Both of these are ballast water transports from the Pontocaspian region. Larger round gobies are specialized for preying on mollusks via crushing molariform teeth. Their predation can be strong enough to deplete dreissenids (Lederer, Massart, and Janssen 2006; Lederer et al. 2008).

Round goby–*H. anomala*. Although these species are both from the Pontocaspian region and they often occupy rocky habitats in the Great Lakes, the round goby seldom feeds on *H. anomala*. Diet analysis in the present study is consistent with the findings of Fitzsimons et al. (2012) which indicated that round gobies lack the biomechanics to feed on elusive mysid prey.

Rainbow smelt–*H. anomala*. Rainbow smelt, native to the North American Atlantic coast, were introduced to a coastal lake in Michigan (1912) from which they escaped into Lake Michigan where they were first reported in 1924 (Hubbs et al. 1958). They prefer colder water, so are generally an offshore species, and they feed primarily on the native mysid, *M. diluviana* (Foltz and Norden 1977). The native mysid does not occur in shallow water, so the invasion by *H. anomala* may be providing a trophic spatial continuity.

Alewife–*H. anomala*. Alewife, native to the North American Atlantic coast, were first found in Lake Michigan in 1948 (Hubbs et al. 1958). They have been the major prey source for Pacific salmons which were introduced in 1966 (coho) and 1967 (Chinook) (Hubbs et al. 1958). Alewife generally prefer warmer water than rainbow smelt, but, they do feed on the native *M. diluviana* when offshore (Janssen and Brandt 1980; Boscarino et al. 2010). Therefore, *H. anomala* may be providing a trophic spatial continuity.

5.2.3 Other

Brown trout–round goby/alewife–*H. anomala*. Based on a few adult brown trout collected, these are feeding on round goby and alewife. This could be a complex interaction, in that divers have occasionally seen juvenile brown trout in caves by day where they might be feeding on *H. anomala*. As they grew, brown trout could possibly transition to feeding on round gobies (year round) and alewife (seasonal), so their presence may increase as the GBW and REF mature.

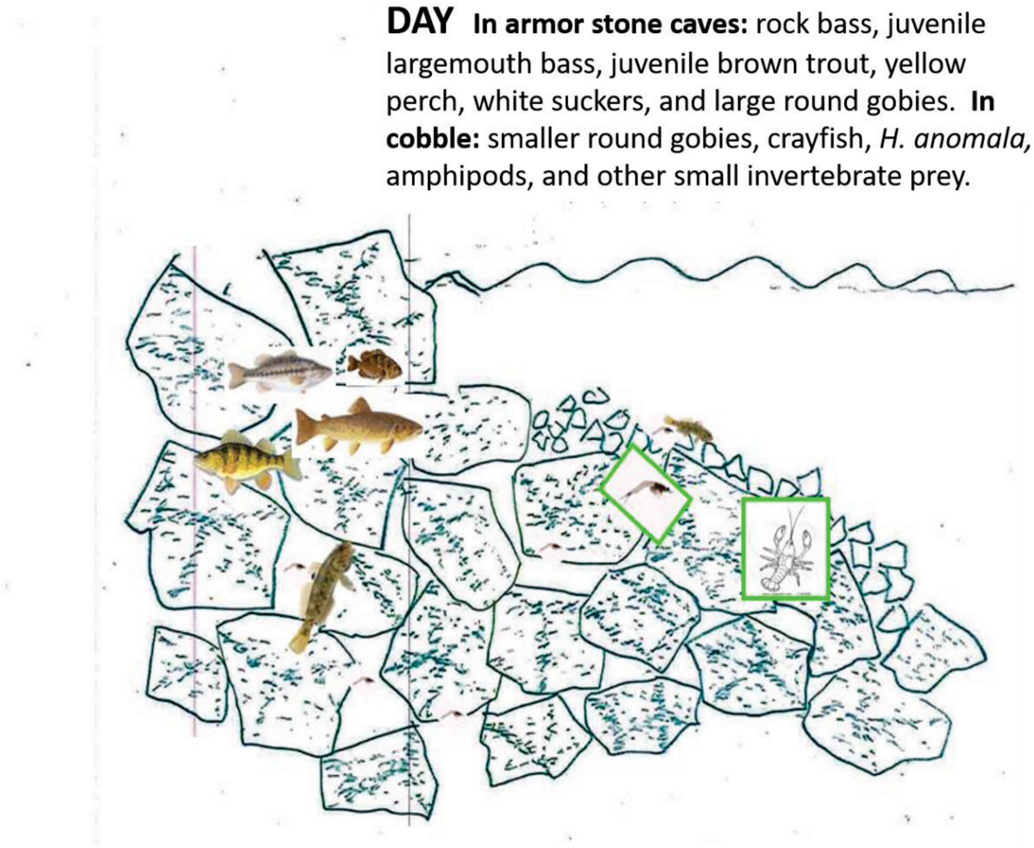
5.3 Diel and lake level–interactions

Combinations of diel behaviors interacting with the physical diversity likely drive the food webs at the GBW and REF, including any differences within those food webs. Water levels also may interact; they affect where there are caves for protection. The importance of these factors will probably remain unknown without *in situ* observations.

5.3.1 Water levels

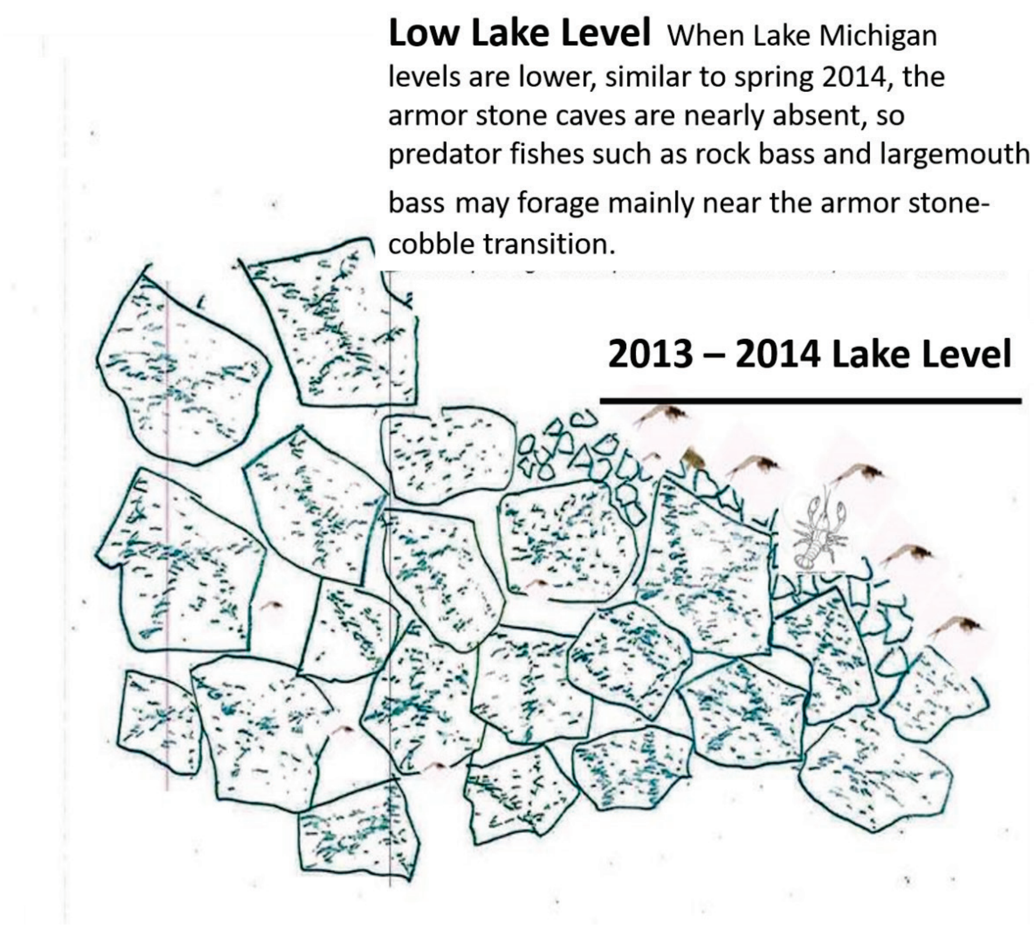
When cobble was deposited at the GBW, its upper extent was near the water's surface, creating cobble that interfaced with armor stone caves at approximately the water's surface. The rise in Lake Michigan water levels created an abundance of submerged caves. The finding of the bass by day was rare, but when they were found, they were inhabiting the caves (figure 26). At night they were very common to see and we think they emerged from the caves to feed at night (figure 27). Juvenile brown trout, rainbow trout, largemouth bass, juvenile to adult yellow perch, and larger round gobies were also found in the caves. At dusk, these species would have ready access to the cobble. During evening dives, abundant *H. anomala* emerged from the cobble; these likely could be ambushed as they emerged, but no direct observations of this occurred (figures 27 and 28).

Figure 26. Species found in the GBW during daylight hours.



DAY **In armor stone caves:** rock bass, juvenile largemouth bass, juvenile brown trout, yellow perch, white suckers, and large round gobies. **In cobble:** smaller round gobies, crayfish, *H. anomala,* amphipods, and other small invertebrate prey.

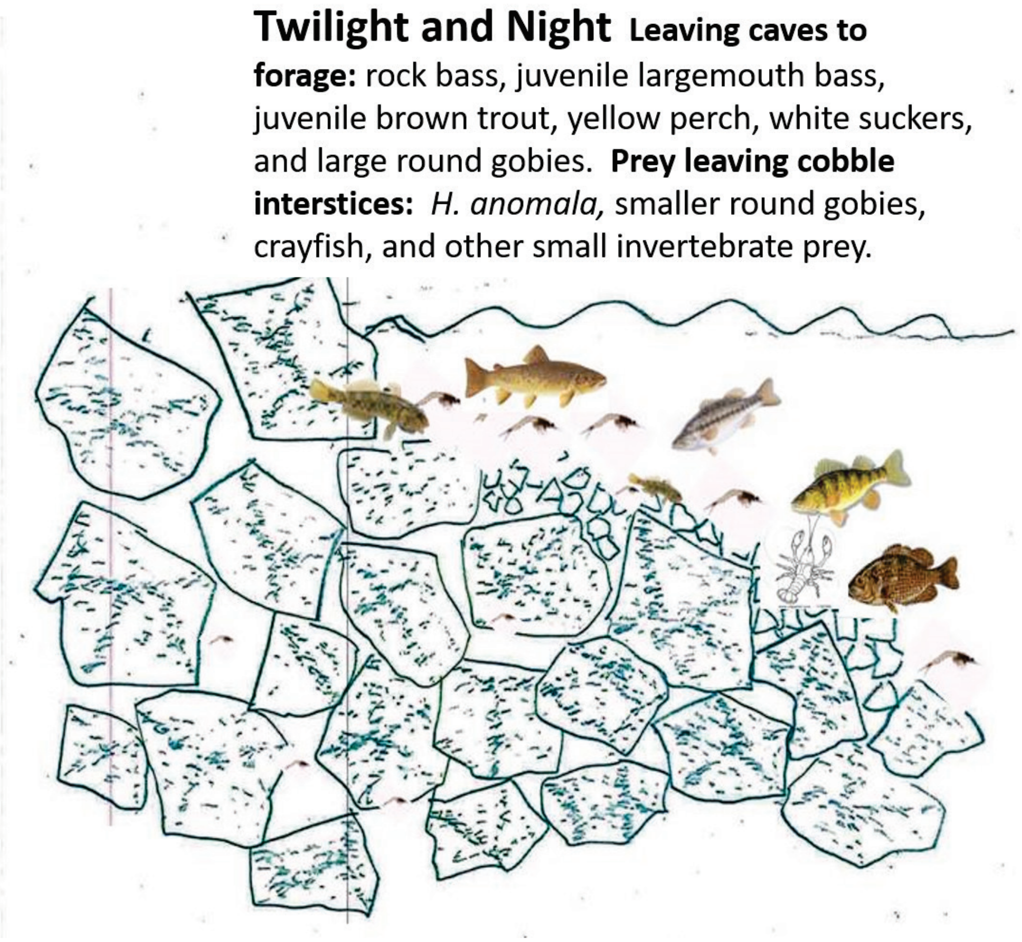
Figure 27. Lake Michigan low lake level showing the inaccessibility of cave habitat among boulders in the GBW.



Low Lake Level When Lake Michigan levels are lower, similar to spring 2014, the armor stone caves are nearly absent, so predator fishes such as rock bass and largemouth bass may forage mainly near the armor stone-cobble transition.

The diel cycle likely interacts with the depth in that, if lake levels had stayed at the level at the time of rock deposition, caves would only be available at the ends of the GBW, so fish such as rock bass would have to swim laterally longer distances to access the entire GBW compared to just swimming downslope a short distance.

Figure 28. Twilight and night foragers within the cobble of the GBW.



Twilight and Night **Leaving caves to forage:** rock bass, juvenile largemouth bass, juvenile brown trout, yellow perch, white suckers, and large round gobies. **Prey leaving cobble interstices:** *H. anomala,* smaller round gobies, crayfish, and other small invertebrate prey.

5.4 Extrapolating to other systems

The GBW and REF are a product of habitat structure combined with the available biota. Where there is a different available biota, the possibilities change; however, some reasonable predictions can be made. This report provides additional information for others to anticipate likely diverse local responses to similar habitat alterations.

An unexpected component of the GBW and REF systems was the abundance of *H. anomala*. Although preliminary observations indicated an abundance in autumn because of the clearly observable aggregations, no indications existed that they might be abundant in late spring to summer. However, upon examining fish diets from that period and conducting night dives, several were observed emerging from the crevices of rocks. Because there is little known about the distribution of *H. anomala* and its relationship to diverse habitats, it is difficult to predict its importance elsewhere. However, *H. anomala* were first discovered at the armor stone breakwater at Muskegan (Pothoven et al. 2007), and subsequently a similar habitat was found at Sheboygan Harbor in summer, 2016 (Eric Geisthardt, University of Wisconsin-Milwaukee, personal observation, 31 August 2016). It is expected that they occur at many other Great Lakes breakwaters.

Until recently, yellow perch would probably have been a very significant component of the GBW and REF. This popular sport fish, which was commercially fished until the mid-1990s, has been in serious decline since the invasion of dreissenids in the early 1990s. Based on limited catch and observations of yellow perch hiding in crevices, it is believed that both habitats might work in conjunction for, at the minimum, local enhancement.

A breakwater with more consistently warmer water would likely host more rock bass, smallmouth bass, and possibly largemouth bass, but on a seasonal (summer) basis. An artificial reef constructed of granite slabs off of Chicago was seasonally occupied by rock bass and smallmouth bass (Creque et al. 2006). The sources are probably various local harbors and a key physical difference with the Milwaukee breakwater is that coldwater upwellings are less common at Chicago, which is at the south end of Lake Michigan.

A more cold-water ensemble of fish species might occur farther north in Lake Michigan; the predictions for this study are based on the WE-Energies reef study (Houghton, Houghton, and Janssen 2013), in which burbot and longnose suckers, both associated with large rocks and colder water, were found to be relatively common and abundant, respectively, compared to a natural reef). At the north end of Lake Michigan, burbot are common enough to have a small commercial fishery. There burbot consume large amounts of round gobies (Hensler, Jude, and He 2008; Hares, Jonas, and Leonard 2015).

The cold water of Lake Superior would likely exclude yellow perch, along with rock bass, smallmouth bass, and largemouth bass. Whether *H. anomala* would be present is uncertain, but it is likely that trout species that associate with rocks could be major occupants.

5.4.1 Reproduction

The original design for the GBW (figure 2) did not contain smaller rock, so it is uncertain how that design would perform. As is, the only species that we are certain were using the breakwater for spawning were alewife (broadcast spawner) and round goby (nest defender). Use by lake trout for spawning is still a possibility given that it can take several years for lake trout to spawn at a new site (Marsden et al. 2016). An issue may be the present instability of the deposited cobble and wave action; these can be factors in spawning site selection by lake trout (Fitzsimons et al. 2007). The original plan for an inlay a few feet deep was probably correct given the reasonable survival to hatching of embryos incubated over the winter in chambers. It may be that significant spawning by lake trout will begin soon. Marsden et al. (2016) found that artificial reefs in Lake Huron took three years before spawning occurred on them.

The occurrence of frequent cold-water upwellings likely kept centrarchids (for example, rock bass, smallmouth bass, and largemouth bass) from spawning at the breakwater. At the islands separating the western and central basins of Lake Erie, storms are a factor that can limit smallmouth bass recruitment (Steinhart et al. 2005), with more sheltered areas being more consistently productive. However, successful smallmouth bass nests at Milwaukee's South Shore Harbor, which is better protected than the main harbor, have been found (Dow 2018).

Exposure to physical and thermal challenges may prove to be a limiting factor with regards to using breakwaters as spawning habitat in the Great Lakes. However, recruitment is also highly dependent on good nursery areas being close by, and the Milwaukee Harbor breakwater, especially the GBW, is providing prey and/or shelter for small fishes.

5.5 Modifications to the GBW design

The unanticipated rise in Lake Michigan's water level created an ecotone between shallower armor stone caves adjacent to the sloping cobble at the GBW. These caves were diurnal homes for rock bass and probably also for the less often seen juvenile brown trout and black basses. With lower water levels, these caves would be absent, and the nearest caves would be adjacent to the north and south ends of the GBW. How far these diurnal cave dwellers would travel from their caves is not known, but the combination of day and night observations suggest that alternating sections of small cobble veneer with standard rubble-mound boulders would enhance utilization of the enhanced breakwater.

6 Conclusions

The USACE EWN breakwater demonstration project in Milwaukee Harbor created complex, rocky aquatic habitat by depositing cobble-sized stone over standard 6–8 metric tons boulders as part of a rubble-mound repair of the breakwater. The demonstration project was largely successful, creating a novel ecosystem benefiting forage fishes and creating nursery habitat for nearshore juvenile game fishes.

This USACE EWN project realized environmental benefits via the introduction of cobble-sized stones (10–20 cm) to cover boulders (6–8 metric tons) along a 152 m section of the breakwater. Monitoring efforts postconstruction revealed that the GBW is home to a prolific population of *H. anomala*, an important food source for local pelagic fishes, including alewife and rainbow smelt. *H. anomala* comprised a significant portion of the diets in YOY yellow perch, YOY largemouth bass, and juvenile rock bass caught on the GBW. The natural features' construction on the GBW increased the available habitat for this benthopelagic macroinvertebrate and created a novel ecosystem—benefiting forage fish and creating a nursery habitat that benefited nearshore game fish juveniles.

Exposure to local hydrodynamic conditions may limit the ability of breakwater modifications to serve as spawning habitat in the Great Lakes. However, recruitment is also highly dependent on good nursery areas being nearby. In the present case, the GBW is providing prey and/or shelter for small fishes.

Monitoring data suggested modifications to the design of the GBW to improve habitat use. Both day and night observations suggest that alternating sections of small-cobble veneer with standard rubble-mound boulders would enhance use of the enhanced breakwater by local fish and invertebrate species.

These data will inform the application of such EWN concepts during structural repairs at other built navigation infrastructure in the Great Lakes and elsewhere.

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Acronyms and Abbreviations

ANOVA	analysis of variance
AOC	areas of concern
BUI	beneficial use impairments
EGN	experimental gill nets
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
EWN	Engineering With Nature
LRE	Detroit District
GBW	Milwaukee Harbor Green Breakwater
RAP	remedial action plan
REF	reference site
ROV	remote-operated vehicle
TL	total length
UWM	University of Wisconsin–Milwaukee
USACE	US Army Corps of Engineers
WDNR	Wisconsin Department of Natural Resources
WE	Wisconsin Energies
YOY	young of the year

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14. ABSTRACT

The US Army Corps of Engineers (USACE) maintains breakwaters in Milwaukee Harbor. USACE's Engineering With Nature® (EWN) breakwater demonstration project created rocky aquatic habitat with cobbles (10–20 cm) covering boulders (6–8 metric tons) along a 152 m section. A prolific population of Hemimysis anomala, an introduced Pontocaspian mysid and important food source for local pelagic fishes, was significantly ($p < .05$) more abundant on cobbles versus boulders. Food-habits data of alewife (Alosa pseudoharengus) and rainbow smelt (Osmerus mordax) provided evidence that H. anomala were a common prey item. Night sur-veys and gill netting confirmed O. mordax preferred foraging on the cob-bles ($p < .05$) and consumed more H. anomala than at the reference site ($p < .05$). H. anomala comprised a significant portion of the diets of young-of-the-year (YOY) yellow perch (Perca flavescens), YOY largemouth bass (Micropterus salmoides), and juvenile rock bass (Ambloplites rupestris) caught on the breakwater. The natural features' construction on the breakwater increased the available habitat for this benthopelagic macroinvertebrate and created a novel ecosystem benefiting forage fish and a nursery habitat benefiting nearshore game fish juveniles. These data will encourage the application of EWN concepts during structural repairs at other built navigation infrastructure

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