Integrated Environmental Assessment and Management — Volume 00, Number 00—pp. 1–14
Received: 29 December 2020 | Returned for Revision: 24 February 2021 | Accepted: 7 April 2021

Special Series

A *Hemimysis*-driven novel ecosystem at a modified rubble-mound breakwater: An Engineering With Nature® Demonstration Project

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EDITOR'S NOTE:

This article is part of the special series "Incorporating Nature-based Solutions to the Built Environment." The series documents the way in which the United Nations Sustainable Development Goal (SDG) targets can be addressed when nature-based solutions (NBS) are incorporated into the built environment. This series presents cutting-edge environmental research and policy solutions that promote sustainability from the perspective of how the science community contributes to SDG implementation through new technologies, assessment and monitoring methods, management best practices, and scientific research.

Abstract

The US Army Corps of Engineers (USACE) repairs aging breakwater structures as part of routine maintenance to maintain safe navigation in Great Lakes commercial ports. A USACE repair to an existing breakwater structure in Milwaukee Harbor (WI) implementing Engineering With Nature (EWN) principles created complex rocky habitat by strategically placing cobble-sized stone over conventional 5.4 to 9.1 metric ton boulders, thus creating "control" (boulder) and "treatment" (cobble) habitats. We evaluated the resultant nature-based breakwater (NBBW) developing food web versus an adjacent reference site on the same breakwater and determined that, unexpectedly, locally abundant *Hemimysis anomala* were impacting the food-web dynamics and feeding ecology of fishes occupying the structure. Fish and forage communities were sampled using gillnets, night scuba diving surveys, rock collections, and a novel trap to capture invertebrates. The resultant NBBW became home to a prolific population of nonindigenous *Hemimysis*, with indications that they were more abundant on cobble versus boulders, based on rainbow smelt feeding. This lithophilic/cave swelling mysid provided an important new food resource in Milwaukee Harbor for two introduced pelagic prey fishes: alewife (*Alosa pseudoharengus*) and rainbow smelt (*Osmerus mordax*). Gillnetting and night scuba diving surveys confirmed that rainbow smelt preferred to forage on the cobble section ($p < 0.05$). *Hemimysis* were also the primary food item consumed by nearshore game fishes such as young-of-the-year (YOY) yellow perch (*Perca flavescens*), YOY largemouth bass (*Micropterus salmoides*), and juvenile rock bass (*Ambloplites rupestris*). We propose that those breakwaters that harbor abundant *Hemimysis* constitute novel ecosystems (ecosystems that include both native and non-native biota) that might benefit harbor fisheries if well-managed. This project demonstrated how a low-cost design modification could be applied during the repair of rubble-mound, breakwater structures to achieve benefits beyond safe navigation. *Integr Environ Assess Manag* 2021;00:1–14. Published 2021. This article is a US Government work and is in the public domain in the USA.

KEYWORDS: *Hemimysis anomala*, Invasive ecology, Lake Michigan, Nature-based feature, Novel ecosystem

INTRODUCTION

Artificial reefs have been popular tools designed to enhance aquatic environments and fishing activities since the early 1900s (Stone, 1974). Though not designed as habitat enhancement, built rocky structures such as breakwaters function as incidental artificial reefs and are typically angler-accessible. This project was a demonstration in modifying a conventional rubble-mound breakwater structure to determine whether it can provide improved fishery and ecosystem benefits.

Rocky substrates are important to benthic and epibenthic organisms for both adherence and cover. In Lake Michigan, rocky habitats are historically known as important for prey used by forage and sport fishes (Houghton & Janssen, 2015;

This article contains online-only Supporting Information.

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Published 15 April 2021 on wileyonlinelibrary.com/journal/ieam.

Janssen & Luebke, 2004; Janssen & Quinn, 1985; Kornis & Janssen, 2011; Marsden et al., 1995; Ray & Corkum, 2001). Natural rocky habitats in Lake Michigan are diverse and include glacially polished bedrock, glacial grooves in such bedrock (often naturally infilled with cobble), talus slopes, and glacial deposits such as drumlins, which all vary in the size, composition, and abundance of interstices (Janssen et al., 2005).

Several of the most impactful, Ponto‐Caspian, non‐native species such as zebra mussels (*Dreissena polymorpha*), quagga mussels (*D. bugensis*), round goby (*Neogobius melanostomus*), and the amphipod *Echinogammarus ischnus,* which have colonized the Laurentian Great Lakes in recent decades, are lithophilic and have substantially altered rocky habitats and the trophic structure of the Great Lakes (Ricciardi & MacIsaac, 2000; Turschak et al., 2014; Vanderploeg et al., 2002). The recently introduced bloody red shrimp, *Hemimysis anomala* (henceforth *Hemimysis*), which has a strong affinity for rocky habitat, has successfully colonized natural and artificial reefs in Lake Michigan (John A. Janssen, personal observations). *Hemimysis* are known to cause substantial changes in food‐web dynamics where they have been introduced in Europe in areas outside their native range (Borcherding et al., 2006; Ketelaars et al., 1999).

The US Army Corps of Engineers (USACE) maintains breakwaters and other built structures important for navigation in commercial ports throughout the Great Lakes. In 2013, the USACE Detroit District (LRE) began repairing the deteriorated breakwater at Milwaukee Harbor as part of annual maintenance. The repair involved placing 5–9 metric ton boulders (armor stone) on the exterior (lakeside) and interior (harbor) sides of the existing sheet pile‐enclosed crib structure. Repairs in 2013 involved adding armor stone along the harbor side to about 580 m (1900 ft) of the 1950‐m (6400‐ft) long structure. As a demonstration for designing environmental enhancements during routine repairs, a nature‐based reef was designed as an ecologically enhanced “nature‐based” breakwater (henceforth NBBW) and constructed by the USACE along the inside of Milwaukee Harbor's outer breakwater via adding cobble substrate as a veneer over a conventional boulder repair where it remains intact (see project summary in Bridges et al., 2018).

The current application of a modified design of a breakwater repair is consistent with Engineering With Nature® (EWN®), a USACE initiative enabling sustainable delivery of economic, social, and environmental benefits associated with water resources infrastructure (Bridges et al., 2014, 2018). Such modifications to the design of the repair of the conventionally built infrastructure support UN Sustainable Development Goal (SDG) #11 that seeks to implement nature‐based solutions to the built environment and SDG #14 on sustainably managing fisheries in coastal ecosystems. Coastal ecosystems in the Great Lakes are very important for several reasons. The coastline of the Great Lakes is vast, extending for 7290 km (4530 mi) (https://coast.noaa.gov/states/fast-facts/great-lakes.html), and the associated commercial, recreational, and tribal fisheries are collectively valued at more than $7 billion annually (http://www.glfc.org/the-fishery.php).

Evaluation of the NBBW was a two‐step process: an initial research plan was executed and modified during 2015, and substantial modifications to the plan were made for 2016. The initial sampling focus was based on prior research on local natural habitat (see above). However, the unanticipated importance of *Hemimysis* in the food web was important enough to shift many sampling methods to focus on understanding their role at the breakwater. We evaluated the developing NBBW food web versus an adjacent reference (REF) site on the same breakwater and determined whether locally abundant *Hemimysis* were impacting the food‐web dynamics and feeding ecology of fishes occupying the Milwaukee Harbor breakwater structure. It is important to note that this study in no way advocates for the introduction of *Hemimysis* or any nonindigenous species to any water body. However, invasive species need to be adequately studied to determine potential impacts and identify containment strategies. An introduced species may have negligible or even positive impacts in one location, but devastating consequences elsewhere.

METHODS

Physical features

The NBBW is a section of modified, rubble‐mound (boulders) breakwater (quarried limestone) located along the inside of Milwaukee Harbor's outer breakwater (Figure 1). Armor‐stone boulders (5–9 metric ton limestone boulders) were deposited along 300 m of the inner breakwater in 2013 and the NBBW cobble veneer was introduced to the southern half (150 m) in April–May 2014 (Figure 2). The northern 150 m served as a REF site. The top of the NBBW cobble lies at less than 2 m in depth, depending on lake levels, and tapers to a depth of about 7 m, where the cobble quickly transitions to silty harbor sediments. Although the harbor has not been extensively mapped, observations of sonar during transit suggest that the maximum depth for the harbor is about 7 m. Much of the cobble veneer is at the critical angle of repose, resulting in occasional storm‐induced rockslides (Geisthardt et al., 2021). However, the cobble veneer remained intact.

In August 2016, an assessment of the NBBW and REF was conducted by Brennan Dow (Univ Wisconsin‐Milwaukee) using a Lowrance HDS10‐Gen 2 with StructureMap HD Sonar Imaging during aquatic habitat mapping efforts in the Milwaukee Harbor. In total, 38 scuba dive surveys and 66 snorkel surveys were conducted at the NBBW and REF during 2015 and 2016.

Temperature

Thermal loggers (HOBO Pendant Temperature 64 K Data Logger) were deployed at the NBBW/REF interface and at the south end of the NBBW in May 2015, and later retrieved via scuba diver or snorkeler in October 2015 and again in June 2016. Each string of temperature loggers consisted of

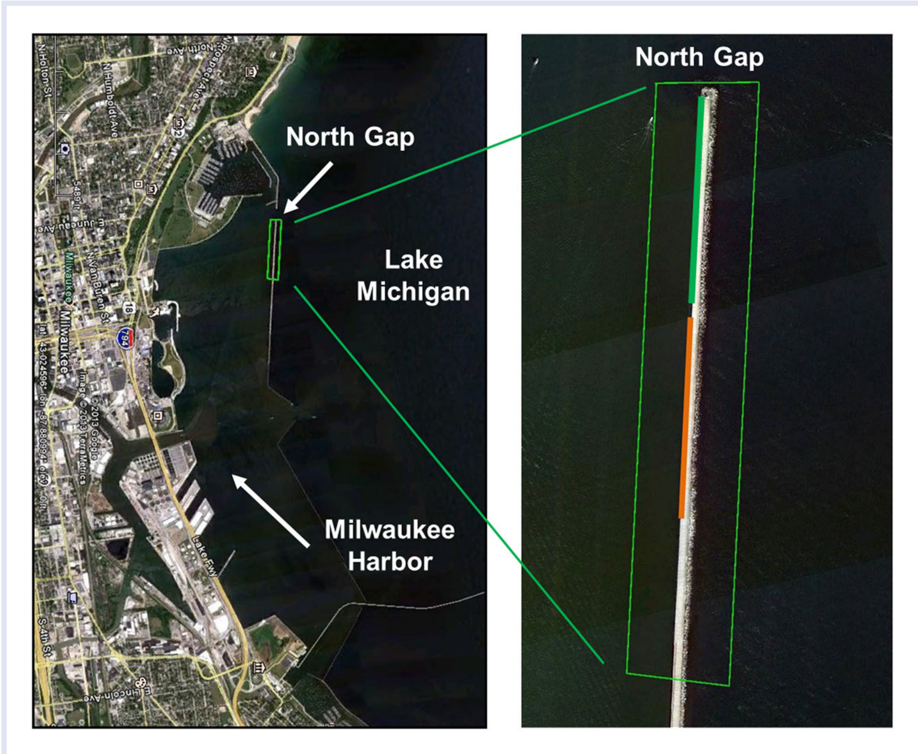

FIGURE 1 Satellite image of Milwaukee Harbor (left) showing the breakwaters that separate the outer harbor from Lake Michigan. The study area (inside the green box on right) with the location of the nature-based breakwater is highlighted in orange and the reference site is highlighted in green

a shallow logger at 2 m, a middle logger at 4 m, and a bottom logger at the base of the NBBW (7 m). Loggers recorded at 5-min intervals during summer months and at 1-h intervals over winter during the isothermal period.

Forage sampling

A novel funnel trap was developed for sampling *Hemimysis* in rocky habitats, as the NBBW and REF are steeply sloped and the REF is highly irregular due to the lack of cobble veneer that prevented the use of traditional plankton towing nets (Geisthardt et al., 2021). The traps were black plastic pails with a 23-cm diameter at the top, 20 cm at the base, and 24-cm height. Each had a black plastic funnel that was 25 cm at the widest (flange) with a cone diameter of 19 cm, opening at its tip 14 mm, and a height of 18 cm, leaving about 5 cm between the tip and the bucket's bottom. Each was weighted with a 1.8-kg iron sash weight across its base and placed where they fit into a rock gap (haphazard). Deployments (11 dates between mid-July and late September) were made on the same day as gillnet sets with five traps set overnight at about 3 m depth on the NBBW and five at the REF. Traps were positioned in cavities among the rocks at 2- to 3-m depth. Captured *Hemimysis* were preserved in 70% ethanol for later enumeration.

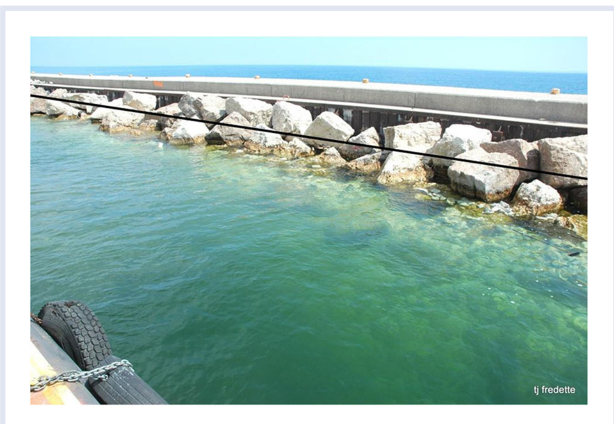

FIGURE 2 A typical section of the Milwaukee Harbor nature-based breakwater (NBBW) shortly after the stone had been deposited in April 2014. The black line approximates the water level for summer, 2015 and 2016, which is about 0.5 m higher. The higher water level created numerous caves in the inundated boulders; these caves were absent at the time of construction. The caves served as cover for diverse fishes for foraging on prey utilizing the adjacent cobble habitat (Photo: Tom Fredette, USACE retired)

Collections of whole cobble (8- to 20-cm diameter) from the veneer were made by scuba divers on September 24, 2015, July 1, 2016, and October 4, 2016, to assess the development of the benthic invertebrate community on the newly placed cobble of the NBBW. Each rock was chosen by touch to assess size (eyes closed) and placed in a cloth bag (eyes now open) whose opening was first wrapped around the rock and then the opening was gathered to surround the rock and sealed with a cable tie. In total, 12 rocks were collected during each sampling event; however, one rock was misplaced during October 2016 and only 11 were processed. Rock samples were processed by rinsing each rock and its bag over a 500-μm sieve to capture attached benthic macroinvertebrates, scraped clean of any mussels and accompanying macroinvertebrates, preserved in 95% ethanol, and then sorted and processed under a dissecting microscope for identification to the lowest practical taxa.

Fish sampling

To compare fish occurrences between the NBBW and REF, biweekly gillnetting took place from June through October in both years. During 2015, experimental mesh gillnets with a range of graded mesh sizes (one net for each site, each net had meshes [bar] of equal lengths of 63.5, 50.8, 38.1, 25.4, and 12.7 mm; the net height was 1.3 m and total length was 150 m) were set overnight. However, experimental gillnets were quite lethal to rock bass (*Ambloplites rupestris*), the most abundant, resident fish. Although rock bass from gillnets were taken for diet analysis, because they typically have a limited home range (Gerking, 1953), it was suspected that repeated experimental gillnetting would substantially impact their abundance. During 2016 (14 dates between early June and late September), graded micromesh gillnets (8 and 6 mm bar; 1.3 m height, 61 m total length) were set to target smaller fishes, because diving observations indicated that the NBBW was likely serving as nursery habitat. During the final five nettings of 2016, an additional 15-m-long gillnet panel of 12.7-mm bar × 1.3-m height was fished with the graded micromesh nets. This larger mesh served to capture alewife (*Alosa pseudoharengus*), rainbow smelt (*Osmerus mordax*), and yellow perch (*Perca flavescens*), which had outgrown the 8-mm-bar mesh as the summer of 2016 progressed.

Nets were set along the rocky slope parallel to the breakwater in approximately 2–3 m of water at both sites. Gillnets were fished overnight from approximately 1600 to 0800 and pulled in the same order as they were deployed to ensure equal sampling times. Captured fishes were promptly removed from the net at shore and live fish were euthanized with an overdose of MS-222 and immediately preserved in 95% ethanol. Fish were sorted by 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 later stomach-content analysis.

Gee-minnow traps were used in 2015 to sample round goby abundance at both sites. On 17 dates between mid-July to late September, five minnow traps baited with dog food were set by snorkelers in 1- to 2-m-depth at both the NBBW and REF to augment gillnetting efforts. Round gobies and bycatch were counted and both total and standard length were recorded.

Night dives were conducted twice in 2015 and seven times in 2016. Initial night dives (2015) revealed that *Hemimysis* was abundant; they were not seen during daytime dives until early August when they commonly formed swarms in boulder caves. During 2016, protocols were established to standardized fish observations along paired transects. During night dives, a pair of divers carrying a dive slate, video camera, and dive lights would work together with one surveying a shallow transect (<4 m) and the other surveying a deep transect (>4 m to base of rocks). Diver courses were sinusoid to cover the depth range. Transects consisted of five, 30-m sections marked with previously set submerged lines on both the NBBW and REF. 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), as well as deep versus shallow dive, were determined randomly.

Analysis of stomach contents was used to examine the developing food web and address whether foraging behavior or diet was different among fishes caught at the NBBW and the REF. Following each gillnet set, a subsample of 10 fish per species per site was separated for stomach-content analysis and preserved in 95% ethanol. If fewer than 10 fish of a species were caught, then all stomachs were removed for analysis. Contents were analyzed under a dissecting microscope, enumerated, and each item was identified to the lowest practical taxa. In the case of round gobies that lack a defined stomach, the entire digestive tract was examined.

Statistical analyses

All analysis of variance (ANOVA) analyses were performed using Systat 10.2 and paired *t* tests were conducted using Excel. For minnow trap collections, a two-factor ANOVA was used to compare $\log(n+1)$-transformed round goby catches by site with Site and Date as main effects and including the Site × Date interaction. Two-factor ANOVAs were run on the number of *Hemimysis* in traps set during 2016 with Date and Site as independent variables and $\log(n+1)$-transformed *Hemimysis* catch. To analyze the numbers of chironomids and amphipods (*E. ischnus*) collected on whole-rock samples at the NBBW from October 4, 2015; July 1, 2016; and September 24, 2016, a one-factor ANOVA was conducted with date as the fixed independent variable and $\log(n+1)$-transformed invertebrate counts as the dependent variable. Post hoc Tukey honestly significant difference multiple comparison tests were used for pairwise comparisons among dates. Two-factor ANOVAs (Site and Date) 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. A paired *t* test compared the total lengths of rock bass caught at the NBBW and REF.

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 main effects and Site × Date, Site × Depth, Date × Depth, and Date × Depth × Site as interactions. For analysis of night dive counts of rock bass and rainbow smelt, we used an ANOVA with Site, Depth, and Date as main effects, and Date × Depth, Depth × Site, Site × Date, and Site × Date × Depth as interaction terms. A two-factor ANOVA was run on the mean number of rock bass at shallow transects at both sites to analyze effects of Temperature, Site, and Temperature × Site interactions.

Diets. For general description of the overall diet in commonly collected species (alewife, rainbow smelt, yellow perch, rock bass, largemouth bass (*Micropterus salmoides*), and round goby), frequency of occurrence ($\%F_i$) and numeric proportion (P_i) were calculated:

$$\%F_i = (N_i/N) \times 100 \text{ and } P_i = S_i/S$$

where N_i is the number of individuals within a species with food item *i* in their stomach and *N* is the total number of fish with stomach contents, and S_i is the total combined number of food item *i* in the stomachs of a species and *S* is the total combined number of all food items consumed by that species. To analyze the consumption of *Hemimysis* by alewife, rock bass, and rainbow trout in 2016, two-factor ANOVAs were conducted with Site and Date as main effects and the Site × Date interaction using $\log(n+1)$-transformed number of *Hemimysis* consumed.

Juvenile alewife less than 90-mm-TL were separated from larger adults for the purposes of stomach analysis, as these smaller fish were all likely aged under 1 year. The 90-mm cutoff for juveniles was established because the length histogram of dissected *A. pseudoharengus* indicated a tightly grouped year class up to this length (Supporting Information Figure S1), and 90 mm was also the maximum size reached by a known-age alewife of the 2015 year class before YOY from 2016 first showed up in gillnets. As not all alewife were aged, no statistical analyses were run to compare age below 1 year with adult alewife.

RESULTS

Temperature

Proximity of NBBW and REF to the North Gap (Figure 1) made it vulnerable to coastal cold-water upwelling events that sometimes caused a rapid change in water temperature. The temperature loggers deployed from June 2015 to October 2016 indicated that the thermal regime at the NBBW and REF differed by less than 2 °C at all times throughout the course of the study. Cold-water upwelling events were frequent in both 2015 and 2016 and sometimes lasted for several weeks (Supporting Information Figure S2). Intensity of upwelling varied but at times caused temperature fluctuations of up to 12 °C over 24-h periods in both years. A thermocline was often present at the beginning of an upwelling event as cool lake water intrusions made their way into the harbor (Supporting Information Figure S2).

Invertebrate forage

Overall, the total number of *Hemimysis* trapped at the NBBW, which we propose as a tentative index of abundance, was approximately twice the catch at the REF (Supporting Information Figure S3), but catches were quite variable. The two-factor (Site and Date) ANOVA, $\log(n+1)$-transformed counts, showed significant effects of date ($F_{10,84} = 3.71$, $p < 0.001$) and Site ($F_{1,84} = 6.8$, $p < 0.011$), but also a significant Date × Site interaction ($F_{10,84} = 2.74$, $p = 0.006$), meaning main effects are difficult to interpret (Zar, 2010). If we make the tenuous assumption that Date is a random factor (Zar, 2010, recommends caution), then the Date × Site interaction is the appropriate *F* ratio denominator and Site is significant ($F_{1,10} = 3.71$, $p = 0.013$) with a conclusion that there were more *Hemimysis* at NBBW than at REF. We regard this statistical result as tentative and report it for the sake of complete reporting. An additional behavioral caution is because, in early August, we began to see *Hemimysis* swarms in breakwater "caves," so it is likely that some *Hemimysis* are swarming at the same time that others are seeking cavities such as the traps at dawn. In rocky habitats outside of the Milwaukee Harbor, we often see swarms of *Hemimysis* associated with boulders as well as single to small groups of *Hemimysis* in cavities under rocks.

The bagged-rock, invertebrate samples' one-factor ANOVAs indicated that both chironomid larvae and *E. ischnus* abundance were statistically significant among the three sampling dates (chironomid $F_{2,32} = 10.2$, $p < 0.001$; *E. ischnus* $F_{2,32} = 33.7$; $p < 0.001$; see Table 1). The Tukey post hoc analyses indicated that chironomid larvae were statistically in greater abundance in 2015 than either date in 2016. Also, *E. ischnus* were statistically more abundant in 2015 than either date in 2016, and the October 4, 2016 sample was also significantly greater than the July 1, 2016 sample. The increase in *E. ischnus* numbers during summer 2016 is probably due to reproduction.

Fish sampling

Gillnetting efforts in 2015 and 2016 revealed a diverse assemblage dominated by the six most common species (excluding the periphyton consuming white sucker (*Catostomus commersonii*) at both sites, making up greater than 98% of the total catch (Table 2). There were 19 species

TABLE 1 Invertebrates captured on whole rocks collected in 2015 from the nature-based breakwater

Date	Rocks sampled	*Echinogammarus ischnus*	Chironomidae larvae
Sep 24, 2015	12	203.6 ± 36.4	4.67 ± 1.85
Jul 1, 2016	12	18.1 ± 4.7	0.08 ± 0.08
Oct 4, 2016	11	46.5 ± 6.4	0 ± 0

Note: Values are the mean ± standard error.

TABLE 2 Total gillnet catches from 2015 and 2016 at the nature-based breakwater (NBBW) and reference (REF) sites

Species	Life history	Utilization	NBBW			REF		
			2015	2016	Total	2015	2016	Total
Alewife *Alosa pseudoharengus*[a]	TO	F	540	919	1459	620	1138	1758
Round Goby *Neogobius melanostomus*[a]	R	F	384	429	813	278	385	663
Rainbow Smelt *Osmerus mordax*[a]	TO	F	6	328	334	6	150	156
Yellow Perch *Perca flavescens*	C	S	2	77	79	6	88	94
Rock Bass *Ambloplites rupestris*	R	S	46	2	48	24	7	31
Largemouth Bass *Micropterus salmoides*	R	S	2	13	15	3	2	5
White Sucker *Catostomus commersonii*	R, TI	F	37	1	38	48	1	49
Gizzard Shad *Dorosoma cepedianum*	R	F	18	0	18	12	0	12
Brown Trout *Salmo trutta*[a]	TI	S	6	0	6	9	0	9
Walleye *Sander vitreum*	R	S	2	0	2	4	0	4
Rainbow Trout *Oncorhynchus mykiss*[a]	TO	S	2	0	2	3	1	4
Lake Trout *Salvelinus namaycush*	TO	S	2	0	2	0	0	0
Green Sunfish *Lepomis cyanellus*	R	N	1	1	2	0	0	0
Golden Shiner *Notemigonus crysoleucus*	R	F	1	0	1	0	0	0
Bluegill *Lepomis macrochirus*	R	S	1	0	1	0	0	0
Shorthead Redhorse *Moxostoma macrolepidotum*	R	N	1	0	1	0	0	0
Common Carp *Cyprinus carpio*[a]	R, TI	N	1	0	1	0	0	0
Spottail Shiner *Notropis hudsonius*	TI	F	0	0	0	0	1	1
Chinook Salmon *Oncorhynchus tshawytscha*[a]	TO	S	0	0	0	0	1	1
Freshwater drum *Aplodinotus grunniens*	R, TI	N	0	1	1	0	0	0
Nine-spine Stickleback *Pungitius pungitius*	TO	F	0	1	1	0	0	0

Note: The white sucker was excluded because it feeds on periphyton. Life Histories include R, resident; TO, transient offshore; TI, transient inshore; C, complex, or a combination of these. Utilization categories are F, forage, S, sportfish (as defined by Wisconsin Department of Natural Resources), and N, non-gamefish. The life history of yellow perch includes offshore transport of larvae (Dettmers et al., 2005) and seasonal movement along the Lake Michigan shoreline.
[a]Non-native species.

caught at the NBBW and 13 species at REF. Eight of the species were known only from a single collection. Alewife and round goby were, respectively, the most abundant fish in both 2015 and 2016; however, different mesh sizes of gillnet were used each year. At the NBBW, alewife composed 51.3% of gillnet catch in 2015 and 51.8% of gillnet catch in 2016. At the REF, alewife composed 61.2% of gillnet catch in 2015 and 64.3% of gillnet catch in 2016.

Alewife was the only species caught during every gillnet set, as well as the most abundant species at each site in both years (Table 2). The two-factor ANOVA (2016; micromesh gillnet sets) had no significant effects for Site ($F_{1,13} = 0.039$, $p = 0.846$) or Date ($F_{13,13} = 1.26$, $p = 0.343$).

Rainbow smelt were the third-most abundant species caught in micromesh nets at both sites in 2016 (Table 2). The two-factor ANOVA showed a significant effect for Date ($F_{13,13} = 9.087$, $p < 0.001$) and Site ($F_{1,13} = 13.65$, $p = 0.003$) with over twice as many rainbow smelt being netted at the NBBW than at the REF in 2016. Catch in gillnets was highest during prolonged upwelling events when cool water was present at the breakwater for several consecutive days (Figure 3).

Rock bass were collected almost exclusively in experimental gillnets in 2015; they were too large for the micromesh nets set in 2016. Rock bass caught at the NBBW were generally smaller than those at the REF (mean TL ± SD of 159 ± 21 mm and 167 ± 30 mm, respectively; however, a paired *t* test (data pooled across dates) indicated that they were not statistically distinguishable ($t_{60} = 1.3$, $p = 0.099$).

Yellow perch catch was almost entirely from micromesh nets set in early September 2016 when age-0 yellow perch typically become demersal after drifting pelagically as larvae and fry (Beletsky et al., 2007; Dettmers et al., 2005; Supporting Information Figure S4). The two-factor ANOVA showed a significant effect for Date ($F_{13,13} = 13.22$, $p < 0.001$), but no significant effect for Site ($F_{1,13} = 0.708$, $p = 0.415$).

Round goby catches in minnow traps in 2015 were highly variable at both sites (Supporting Information Figure S5; also

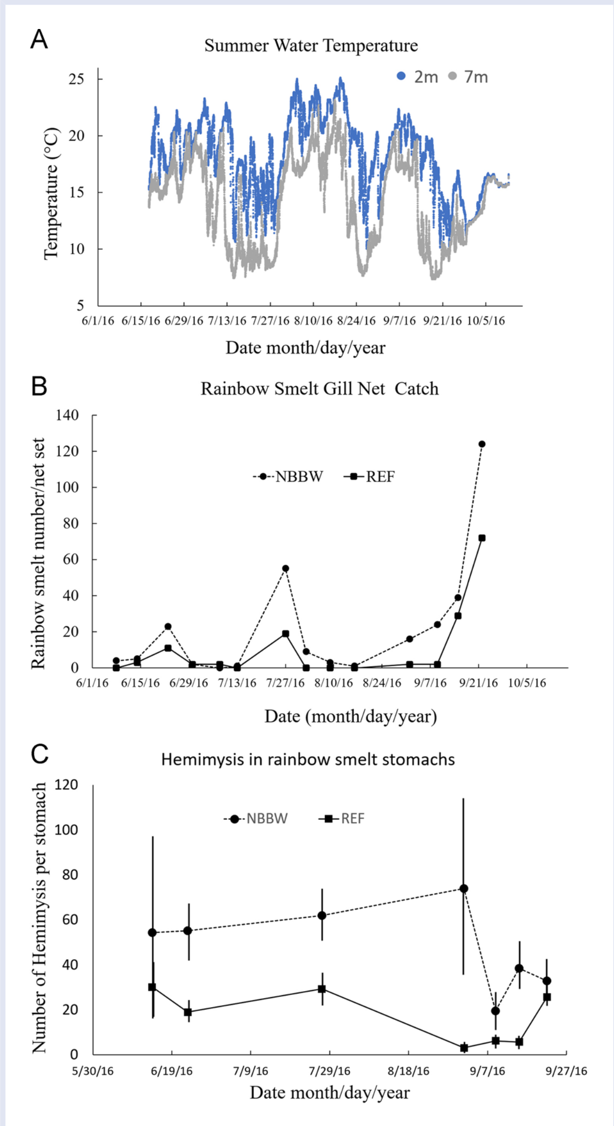

FIGURE 3 (A) Surface and bottom water temperatures for summer 2016 at the interface of the nature-based breakwater (NBBW) and reference (REF) sites. (B) Rainbow smelt (*Osmerus mordax*) catch in gillnets at NBBW and REF. (C) Number (mean ± standard error) of *Hemimysis* per rainbow smelt stomach at the NBBW and REF

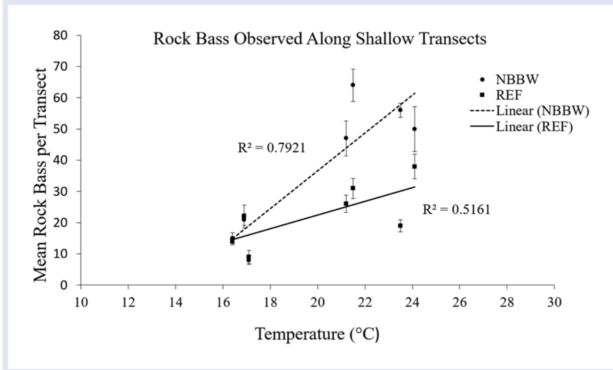

FIGURE 4 Rock bass (*Ambloplites rupestris*) observed in the shallower half of the Milwaukee Harbor nature-based breakwater (NBBW) and reference (REF) sites during night dives in relation to shallow temperature. It should be noted that there is a trend toward more rock bass with warmer water and that there tended to be more rock bass seen on the NBBW as compared with REF. Values are the mean ± standard error

see Geisthardt et al., 2021). The two-factor ANOVA showed a not significant Site × Date interaction ($F_{16, 132} = 0.69$, $p = 0.8$) and both main effects were significant (Site, NBBW > REF, $F_{1, 132} = 4.55$, $p = 0.035$; Date: $F_{16, 132} = 2.18$, $p = 0.008$). Round goby micromesh gillnet catches from 2016 had no significant effects for both Site ($F_{1, 13} = 1.15$, $p = 0.303$) and Date ($F_{13, 13} = 2.06$, $p = 0.102$).

Night dives

During night dives, the two fishes most easily counted were rock bass and rainbow smelt because neither was actively swimming. Alewife was too active for divers to accurately count and round gobies were hiding in complex crevices, making accurate counts difficult. For these reasons, we abandoned night surveying for alewife and round gobies, which would have required multiple dives per night.

During the initial night dive on July 8, 2015, we first observed the emergence of *Hemimysis* from the cavities in the cobble of the NBBW shortly after dusk. Until this point, no *Hemimysis* had been observed, though they were common in rock bass and alewife stomachs. Divers observed *Hemimysis* emergence from NBBW crevices during every night dive in 2016 and, once dark, they were abundant at both NBBW and REF.

Rock bass sightings increased in relation to water temperature (Figure 4). The significant interaction between Site × Temperature ($F_{1, 10} = 5.28$, $p = 0.044$) from a two-factor ANOVA indicated that the positive relationship between increased temperature and mean rock bass/transect was greater at the NBBW than at the REF. A three-factor ANOVA with Site, Date, and Depth as factors (Supporting Information Table S1) confirmed that there was a significant Site × Depth interaction ($F_{1, 112} = 8.19$, $p = 0.005$). Rock bass position at both the NBBW and REF was often related to the presence and depth of the thermocline. Complexity was indicated by the significant Site × Depth × Date interaction ($F_{6, 112} = 3.33, p < 0.005$), probably interpretable as temperature affecting rock bass observability.

For rainbow smelt, a three-factor (Date, Depth, and Site, including all interactions) ANOVA conducted on $\log(n + 1)$-transformed night dive observations of rainbow smelt indicated that all interactions between factors as well as the three main effects were significant (Supporting Information Table S1) and the significant Site × Depth × Date interaction indicates complexity. As with rock bass, the complexity seems to be best explained by temperature (Figure 3), particularly the presence and depth of the thermocline. Rainbow smelt was always more abundant along the deep transect in the hypolimnion at both sites and was often below 50 cm from the bottom.

Diet study

Hemimysis were observed as the main prey items in the fish stomachs of alewife (adults and juveniles, rainbow smelt, yellow perch, rock bass, and largemouth bass (Table 3).

TABLE 3 *Hemimysis anomala* in stomachs from a subsample of fish caught during gillnetting during 2015 and 2016

	Juv. alewife		Adult alewife		Rainbow smelt		Yellow perch		Rock bass		Largemouth bass		Round goby	
	%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
REF prey *item*														
Mysidacea														
H. anomala Adult	42	0.12	55	0.42	88	0.41	60	0.23	43	0.85	100	0.85	1	<0.01
H. anomala Juv.	7	<0.01	16	0.02	26	0.05	47	0.21	5	0.02	20	0.13	0	0
Number of fish examined	73		122		68		61		27		5		158	
Percent empty	22		21		16		13		22		0		25	
Mean TL ± SD (mm)	78 ± 8		137 ± 23		128 ± 22		95 ± 42		167 ± 30		52 ± 8		73 ± 18	
NBBW prey *item*														
Mysidacea														
H. anomala Adult	37	0.07	71	0.53	88	0.54	53	0.10	59	0.97	44	0.09	6	0.01
H. anomala Juv.	14	0.02	17	0.02	37	0.23	38	0.23	0	0	56	0.89	0	0
Number of fish examined	98		154		98		52		46		13		181	
Percent empty	19		22		17		23		41		31		30	
Mean TL ± SD) (mm)	76 ± 9		136 ± 22		127 ± 23		81 ± 29		159 ± 21		74 ± 22		73 ± 26	

Note: Shown are results from the six most abundant fish species, excluding the periphyton feeding white sucker and gizzard shad. Prey items are measured in frequency of occurrence (%F_i) in fish without empty stomachs and numerical proportion (P_i) of an item in the diet. Five of the six species fed mainly on *Hemimysis*; the exception was round goby, which fed mainly on amphipods and dreissenid mussels. Results of the full analysis are presented in Supporting Information Tables S2 and S3.
Abbreviations: Juv., juvenile; NBBW, nature-based breakwater; REF, reference; SD, standard deviation; TL, total length.

Round gobies, which had mainly dreissenids as prey, are included in Table 3. Complete diet tables for these six most abundant species are presented in Supporting Information Tables S2 and S3.

Alewife fed heavily on *Hemimysis* at both the NBBW and REF throughout the study, and *Hemimysis* were numerically the most abundant food item consumed at both sites. Both the frequency of occurrence and proportion of *Hemimysis* in adult alewife stomachs were greater on the NBBW than at the REF (Table 3). The two-factor ANOVA analyzing *Hemimysis* consumption by alewife showed a significant Date effect ($F_{9,107} = 3.62$, $p = 0.001$), but there was no significant effect for either Site ($F_{1,107} = 0.072$, $p = 0.789$) or the Site × Date interaction ($F_{9,107} = 1.747$, $p = 0.087$).

Rainbow smelt in 2015 and 2016 fed primarily on *Hemimysis* at both sites ($P_i = 0.77$ at NBBW and $P_i = 0.46$ at REF). Rainbow smelt at the REF tended to consume more zooplankton at the REF than they did at the NBBW (REF: $P_i = 0.52$, NBBW: $P_i = 0.22$). Both the frequency of occurrence and proportion of *Hemimysis* in rainbow smelt stomachs were greater on the NBBW than at the REF (Table 3 and Figure 3). The two-factor ANOVA analyzing rainbow smelt consumption of *Hemimysis* (2016) indicated significant effects of both date ($F_{1,78} = 3.57$, $p = 0.004$) and Site ($F_{1,78} = 7.38$, $p = 0.008$), but no significant Site × Date interaction ($F_{6,78} = 0.934$, $p = 0.47$) was observed.

Rock bass captured in 2015 gillnetting consumed primarily *Hemimysis* at both sites (REF: $P_i = 0.87$, NBBW: $P_i = 0.97$). The two-factor ANOVA showed no significant effects for either Date ($F_{9,14} = 1.52$, $p = 0.233$) or Site ($F_{1,14} = 0.282$, $p = 0.604$). As the sample size was small and many dates lacked paired data, we could not test for the significance of Site × Date interactions. The second major prey item of rock bass at both study sites was juvenile round goby, which had the same frequency of occurrence as *Hemimysis* ($F_i = 43\%$) in REF fish.

A majority of the yellow perch gillnetted were of age 0, which had recently returned to shore, post-larval/juvenile drift. In the pelagic stage in Lake Michigan, age-0 yellow perch feed primarily on zooplankton, making the shift to benthic invertebrates after they return to nearshore habitats (Dettmers et al., 2005). Many of these age-0 yellow perch may have been too small to forage on the elusive adult *Hemimysis,* but were able to consume juvenile *Hemimysis* that are typically 1–2 mm in length, similar in size to the mobile calanoid copepods that yellow perch fed heavily on at both Sites (REF: $P_i = 0.54$, NBBW: $P_i = 0.66$). A few YOY yellow perch gorged on juvenile *Hemimysis*, with one individual caught on the NBBW consuming 291 juvenile *Hemimysis* accounting for 52% of all juvenile *Hemimysis* consumed by yellow perch at the NBBW. The same was true at the REF, where four of the yellow perch sampled contained 53% of all juvenile *Hemimysis*.

Few largemouth bass, of age 0, were sampled at both sites during the study (REF: $N = 5$, NBBW: $N = 13$). Those that were netted fed almost exclusively on *Hemimysis* (Supporting Information Table 3, $P_i = 0.98$ for both sites).

Round goby

Round gobies were numerous and most frequently fed on dreissenid mussels ($F_i = 79\%$ at REF and $F_i = 70\%$ at NBBW). Benthic chydroids cladocerans were the second most frequently encountered forage and were numerically the most abundant item in round goby stomachs owing to their small size relative to dreissenid mussels ($P_i = 71\%$ at REF and $P_i = 60\%$ at NBBW). The next most important prey at both NBBW and REF was in nonindigenous amphipod *Echinogammarus.* There were no significant differences in diet between round gobies collected from the NBBW and REF sites (Tables S2 and S3).

DISCUSSION

As a consequence of the unanticipated importance of *Hemimysis* as prey for diverse fishes, our assessment proceeded in two stages, with a shift to an improved understanding of the *Hemimysis* role in 2016. The initial assessment design, essentially the methods for 2015, was based on what little is understood about the ecology of Great Lakes rocky habitats that have been poorly inventoried and studied (Janssen et al., 2005). Thus, for forage invertebrates, we focused on midge emergence (Kornis & Janssen, 2011), crayfish (Janssen & Quinn, 1985; Quinn & Janssen, 1989), and rock-associated midge larvae, amphipods, and isopods (Houghton & Janssen, 2015; Janssen & Quinn, 1985). The major findings for 2015, however, were that the most abundant primary forage species was *Hemimysis*. Consequently, our discussion focuses on the second year's (2016) research where we more specifically targeted the *Hemimysis*-based food web. A more complete report can be found in Geisthardt et al. (2021). Overall, our two-year assessment has impacts on predictive and assessment outcomes of future NBBW and coastal artificial reef projects in the Great Lakes, but it also impacts our understanding of their naturally diverse rocky areas.

Considering our 2016 observations, we propose that both the NBBW and REF are best considered as without an appropriate natural model for comparison, hence "novel ecosystems" (Hobbs et al., 2013; Marris, 2009). The working definition from Hobbs et al. (2013) is as follows: "A novel ecosystem is a system of abiotic, biotic and social components that, by virtue of human influence, differ from those that prevailed historically, having a tendency to self-organize and manifest novel qualities without intensive human management."

In the review by Marris (2009) novel ecosystem biota consist of both native and non-native species. The major prey for five of the six primary fishes observed on the NBBW and REF was the nonindigenous *Hemimysis anomala* from the Ponto-Caspian region. Two of the primary five fishes, alewife and rainbow smelt, are pelagic species introduced from the North American Atlantic coast. Both are important Great Lakes species for native and introduced trouts and salmons. The third non-native fish is the round goby, which is a coastal benthic species with the same Ponto-Caspian origins as its major prey in our study, dreissenid mussels. Rock bass and largemouth bass are native harbor (estuarine) residents. Yellow perch, also native, were formally abundant coastal and harbor species (see Dettmers et al., 2005).

The surprising association of the pelagic alewife and rainbow smelt with rocky habitat is, we argue, based on the abundant *Hemimysis* prey and not the rocks per se. Cold-water upwellings were associated with the presence of rainbow smelt. The native mysid, *Mysis diluviana*, is a major prey when these two species are offshore in cold water, with both species feeding on them at night (Boscarino et al., 2010; Foltz & Norden, 1977; Janssen & Brandt, 1980), so the addition of *Hemimysis* to the breakwater may create an inshore/offshore mysid continuum in terms of familiarity with a prey type.

Consistent with the definition by Hobbs et al. (2013) of "novel ecosystems" for NBBW and REF, the novel abiotic component is a complex, continuous network of "caves" formed by adjacent quarried limestone boulders. The continuous nature of the caves is more apparent at REF because the view is not blocked by the cobble veneer. Some cave entrances are large enough for a diver to partially enter, but we avoided entering for safety concerns. However, using a dive light by day revealed *Hemimysis* swarms deep within these caves by early August. Rock bass, round gobies, and occasionally unidentified trout also occupied these same cavities. For NBBW, the habitat is enhanced by the addition of the cobble veneer as a "nature-based" feature. However, underlying this veneer, there are large caves between the subtending armor stones. These caves can be seen by peering through openings between armor stone at the shallow edge of the veneer. These caves with the cobble veneer "roof" also have *Hemimysis* swarms.

The last two sentences are added to point out that the Claramunt et al. (2012) reef is not like NBBW. In a review of naturally occurring rocky areas of Lake Michigan (Janssen et al., 2005), there were no known natural features like either NBBW or REF. Natural rocky habitats include glacially polished and/or cracked bedrock, glacial grooves in such bedrock typically infilled with cobble, talus slopes, and glacial deposits (Janssen et al., 2005). Glacial deposits such as drumlins can have much interstitial space (Riley et al., 2014, 2017), so drumlins may be the closest analog to boulder breakwaters. Rocks of the size of Milwaukee Harbor's breakwater boulders can be found but scattered and not abutting, so they do not form caves. Likely the best-studied natural reef with regard to *Hemimysis* is the one reported by Claramunt et al. (2012) in Traverse Bay, Lake Michigan. This has deep layers of cobble with abundant interstitial space, but it is not subtended by caves formed between large boulders (John A. Janssen scuba observations with Claramunt present, September 2014).

We argue that the breakwater is an abiotic novelty in the context of Marris (2009). By placing the cobble veneer over the boulders, the NBBW offers a more natural-appearing habitat than the conventional boulder breakwater repair (REF) but does not strictly "mimic" natural rocky habitat occurring in Lake Michigan. The physical attributes of rubble-mound breakwater structures (size, depth, and slope of rock placement) in the Great Lakes limit what nature-based features can be efficiently incorporated into the design of the structure's repair.

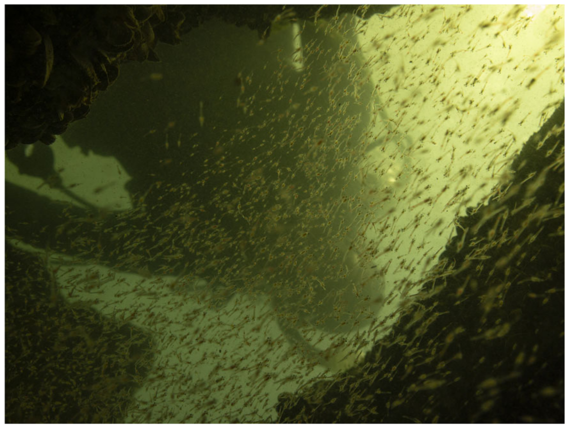

FIGURE 5 Rock bass/small trout, about noon, view of a *Hemimysis* swarm in a breakwater boulder cave observed in Port Washington Harbor, Wisconsin (September 2020). This swarm was similar to those observed on the Milwaukee Harbor breakwater in 2016 (Photo: Jeff Houghton, Univ Wisconsin-Milwaukee)

From the perspective of *Hemimysis*, it was not the boulders per se that were novel habitat; instead, it was the "caves" between boulders, as illustrated by Figure 5, which is a view looking up from a "cave" full of *Hemimysis*. The *Hemimysis* are not in contact with the boulders, so the shaded cavity is the important feature, not the walls. The presence and diversity of caves likely explain the abundance of *Hemimysis* because its congeners include several cave dwellers (Rastorgueff et al., 2011). During daytime dives, using a flashlight to peer into the caves, we frequently saw mostly rock bass and round gobies, but also yellow perch and small brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) deep within the caves. We suspect that especially rock bass and round gobies captured in gillnets emerged from caves at night. More pelagic fishes such as alewife and rainbow smelt were never seen in caves.

Our research points to the need for a better understanding of the relationship between *Hemimysis*, diverse hard substrate, and cavities of varying characteristics. Our trap data suggest that *Hemimysis* tended to be more abundant at NBBW than at REF, but with statistical caveats. Brown et al. (2017) used both unlighted and lighted traps and had no evidence that either trap was quantitative. Given how variable catches were in our traps and those of Brown et al. (2017), if they can provide relative density comparisons, it may require very large sample sizes to compare sites. Given the patchiness of *Hemimysis* (our observations and those of Brown et al., 2012 for Seneca Lake), it is likely that large sample sizes would be needed for statistical robustness, along with data transformations targeting contagious distributions, to detect density differences of consequence (Elliott, 1971). Perhaps the best indicator that NBBW had higher densities of *Hemimysis* was the consistent higher numbers of *Hemimysis* in rainbow smelt stomachs.

Although natural collections of large boulders creating extensive "caves" appear to be a rare to nonexistent natural situation, their presence at artificial structures in other harbors (de Lafontaine et al., 2012) may offer clues to how *Hemimysis* recognizes appropriate habitat. Anecdotally, we commonly see dozens to hundreds of *Hemimysis* beneath individual natural loose cobble of a size similar to the NBBW cobble in the Lake Michigan coastal area. We argue that the NBBW modification of this boulder breakwater, specifically the addition of loose cobble that overlies large interstices, facilitates *Hemimysis* utilization. *Hemimysis* are crepuscular, remaining in the shelter of rocks and cavities by day and emerging as darkness ensues. At REF, the cave openings are large, whereas, at NBBW, these large openings are covered by loose cobble. This means that emergence at the NBBW is from much smaller passages than at REF. So it is possible that there is a preference for the complex heterogeneous cavities in the NBBW and this may facilitate local success of *Hemimysis*, as nearly twice as many adults and juveniles were caught at the NBBW than at the REF (again noting statistical caution). A complicating factor that we did not actively study was that *Hemimysis* exhibited swarming behavior beginning in early August of both 2015 and 2016 and swarms were continuously observed through mid-November when fieldwork ceased.

Food webs vary considerably in freshwater systems as a consequence of diverse habitats and what species are locally available (Ross, 2013). For the Milwaukee breakwater, Figure 6 shows a hypothesized food web. Focusing on the six most abundant fishes (excluding the periphyton-consuming white sucker), a "bottom-up" approach to the food web would likely have *Hemimysis* and dreissenid mussels as primary consumers. Dreissenids are suspension feeders on phytoplankton, and we found *Hemimysis* would graze on tufts of *Cladophora* and their fecal pellets consisted of adnate diatom frustules. *Hemimysis* were then prey for two pelagic nonindigenous transient forage species (alewife and rainbow smelt) as well as native sport fishes (rock bass, yellow perch, and juvenile largemouth bass). Round gobies are prey for larger rock bass, yellow perch, and largemouth bass (Madenjian et al., 2019).

It is likely that *Hemimysis*-based novel ecosystems are common in the Great Lakes but with variations in local food webs. Dives conducted along the inner rubble-mound (boulder) breakwaters at other harbors in western Lake Michigan (Kenosha, Port Washington, Sheboygan, and Manitowoc, Wisconsin) in August and September 2020 indicated the presence of *Hemimysis* swarms at about 3 m of water depth within the caves of these structures (John A. Janssen, personal observations; Figure 5). For these harbors, the fishes that *Hemimysis* might support as prey are likely the same as for Milwaukee.

Laboratory work on what fishes can capture *Hemimysis*, which like *Mysis diluviana* is highly evasive (Janssen, 1978), could facilitate understanding nuances such as the lack of *Hemimysis* in the diet of round gobies. Boscarino et al. (2020) found that round gobies had the lowest feeding rate of the several fishes they tested. Alewife had the highest feeding rate. Where it is warmer, it is likely that black basses

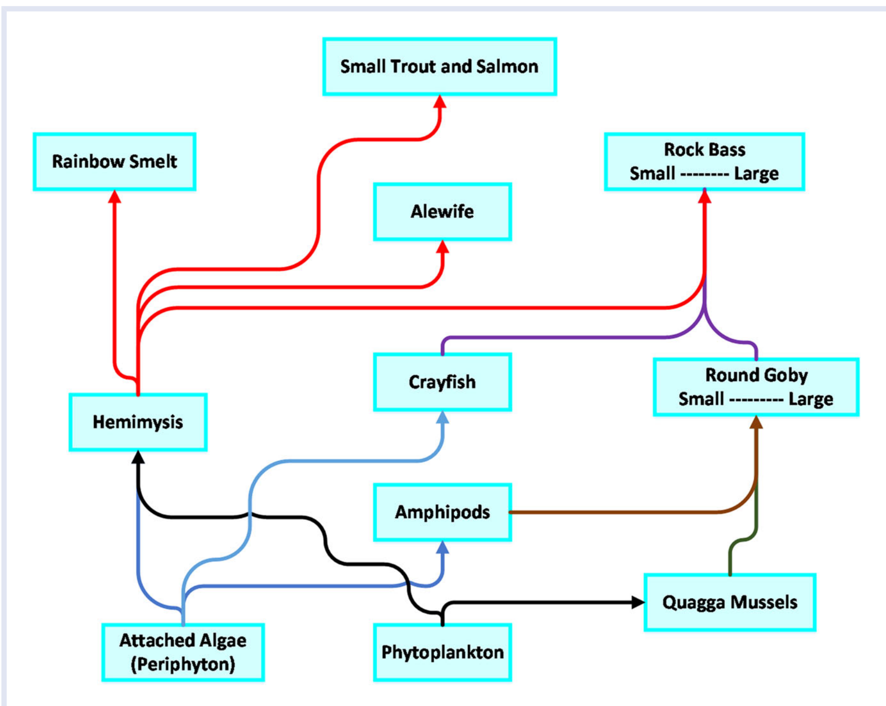

FIGURE 6 Proposed food web featuring the species most consistently observed on the reference and nature-based breakwater sites on the breakwater in Milwaukee Harbor

(*Micropterus* spp.) YOY might be more common than we found. An interesting possibility would be if the release of stocked trouts and salmons could take advantage of this new prey source.

Previous inventory of biota at naturally rocky habitat in Lake Michigan, which does include the same introduced species as the NBBW and REF sites (Janssen et al., 2005), did assist in predicting what fish species were present. However, the importance of *Hemimysis* in the diet of diverse fishes was not anticipated when the study began in 2015. Houghton and Janssen (2015) did find *Hemimysis* in the diets of age-0 yellow perch, but they were never abundant.

We emphasize that our finding that an invasive species, *Hemimysis anomala*, is the primary forage at the Milwaukee breakwater, particularly the NBBW, is not an endorsement for introducing nonindigenous species. The Great Lakes have had a long and ongoing history of adapting to both nonintentional and intentional nonindigenous species introductions (Mills et al., 1993; Sturtevant et al., 2019). Of the 21 fishes collected, seven are nonindigenous. Four of the introduced species (common carp, rainbow trout, brown trout, and Chinook salmon) were intentionally introduced, and the salmon and two trouts forage primarily on three of the accidentally introduced species (alewife, rainbow smelt, and round goby). In fact, management of alewife and rainbow smelt is based on managing introduced salmon and trout management (Madenjian et al., 2019). In their concluding discussion of novel ecosystems, Hobbs et al. (2013) argued: "…. that these novel systems will require significant revision of conservation and restoration norms and practices away from the traditional place-based focus on existing or historical assemblages." As the Great Lakes are already managed for a mix of native and introduced species, productive management of physical interfaces of human and natural systems such as breakwaters is consistent with ongoing practices.

CONCLUSION

This application of a modified design of a breakwater repair is consistent with EWN®, a USACE initiative enabling sustainable delivery of economic, social, and environmental benefits associated with water resources infrastructure (Bridges et al., 2014, 2018). The EWN principles addressed through the implementation of the current project include the use of science and engineering to produce operational efficiencies supporting sustainable delivery of project benefits. The added project costs were only about 10% greater while contributing enhanced aquatic habitat benefits beyond incidental associated with the conventional boulder repair. Natural processes were used to maximum benefit, thereby reducing demands on limited resources, minimizing the environmental footprint of the project, and enhancing project value. The cobble was locally sourced and represented a nature-based feature that was designed to mimic a natural rocky bottom habitat that enhanced aquatic habitat value.

ACKNOWLEDGMENT

Assistance in fieldwork was provided by Ryan Glasford, Chris Groff, Chris Suchocki, Dylan Olson, Ben Turschak, Brennan Dow, and Finton Kat. Special thanks are extended to Mr. Paul Bijhouwer and Mr. Rich Ruby (USACE Buffalo District), Mr. Hal Harrington and Mr. Jon Imbrunone (USACE Detroit District), and Mr. Bob Stanick, and the USACE Detroit District Floating Plant crew for assistance in the design and construction of the demonstration project. Mr. Will Wawrzyn (formerly of Wisconsin Department of Natural Resources) provided expert technical advice. This study was funded by the USACE Engineering with Nature initiative, US Army Engineer Research and Development Center (ERDC) Dredging Operations and Environmental Research program, Todd Bridges, Program Manager, and Salmon Unlimited. The peer review for this article was managed by the Editorial Board without the involvement of Burton C Suedel.

CONFLICT OF INTEREST

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

Data are available upon request from author John A. Janssen at jjanssen@uwm.edu.

SUPPORTING INFORMATION

TABLE S1. Three-factor ANOVA analyzing the $\log(n+1)$ transformed number of rock bass (*Ambloplites rupestris*) and rainbow smelt (*Osmerus mordax*) observed on night dives in 2016 at the Milwaukee Harbor nature-based breakwater (NBBW) and reference (REF) sites and at two different depths (shallow [2 m] and deep [7 m]).

TABLE S2. Milwaukee Harbor reference (REF) site stomach contents from a subsample of fish caught during gill netting during 2015 and 2016. Prey items were measured in frequency of occurrence ($\%F_i$) 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.

TABLE S3. Milwaukee Harbor nature-based breakwater (NBBW) stomach contents from subsamples of fish caught during gill netting in 2015 and 2016. Prey items are measured in frequency of occurrence ($\%F_i$) in fish without empty stomachs, and numerical proportion (P_i) of an item in the diet. Other taxa consumed at the GBW included Alewife, Hydropsychidae, Hydracarinidae, Harpacticoida, Isopoda, and diatoms.

FIGURE S1. Alewife (*Alosa pseudoharengus*) total length (TL) histogram from fish with stomachs sampled in 2016 indicating a year class of age <1 alewife between 70- and 90-mm TL.

FIGURE S2. 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 green breakwater. Note that in both summer 2015 and 2016 there are wide temperature fluctuations corresponding to coastal upwellings and downwellings.

FIGURE S3. Total (all size and sex categories) *Hemimysis anomala* per trap by date. Values are the mean ± standard error.

FIGURE S4. Gill net catch of yellow perch *(Perca flavescens)* during summer 2016.

FIGURE S5. Round goby (*Neogobius melanostomus*) catch from baited minnow traps set in 2015. Values are the mean ± standard error.

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REFERENCES

Beletsky, D., Mason, D. M., Schwab, D. J., Rutherford, E. S., Janssen, J., Clapp, D. F., & Dettmers, J. M. (2007). Biophysical model of larval yellow perch advection and settlement in Lake Michigan. *Journal of Great Lakes Research*, *33*, 842–866.

Borcherding, J., Murawski, S., & Arndt, H. (2006). Population ecology, vertical migration and feeding of the Ponto-Caspian invader *Hemimysis anomala* in a gravel-pit lake connected to the River Rhine. *Freshwater Biology*, *51*, 2376–2387.

Boscarino, B. T., Oyagi, S., Stapylton, E. K., McKeon, K. E., Michels, N. O., Cushman, S. F., & Brown, M. E. (2020). The influence of light, substrate, and fish on the habitat preferences of the invasive bloody red shrimp, *Hemimysis anomala*. *Journal of Great Lakes Research*, *46*, 311–322.

Boscarino, B. T., Rudstam, L. G., Tirabassi, J., Janssen, J., & Loew, E. R. (2010). Light effects on alewife-mysid interactions in Lake Ontario: A combined sensory physiology, behavioral, and spatial approach. *Limnology and Oceanography*, *55*, 2061–2072.

Bridges, T. S., Bourne, E. M., King, J. K., Kuzminski, H. K., Moyniham, E. B., & Suedel, B. C. (2018). *Engineering with Nature®: An Atlas. ERDC/EL SR-18-8*. U.S. Army Engineer Research and Development Center. https://doi.org/10.21079/11681/27929

Bridges, T. S., Lillycrop, J., Wilson, J. R., Fredette, T. J., Suedel, B. C., Banks, C. J., & Russo, E. J. (2014). Engineering With Nature promotes triple-win outcomes. *Terra et Aqua*, *135*, 17–23.

Brown, M., Roth, J., Smith, B., & Boscarino, B. (2017). The light at the end of the funnel?: Using light-based traps for the detection and collection of a nearshore aquatic, invasive invertebrate, *Hemimysis anomala*. *Journal of Great Lakes Research*, *43*, 717–727.

Brown, M. E., Morse, R., & O'Neill, K. (2012). Spatial, seasonal, and diel distribution patterns of *Hemimysis anomala* in New York State's Finger Lakes. *Journal of Great Lakes Research*, *38*, 19–24.

Claramunt, R. M., Barton, N. T., Fitzsimons, J. D., & Galarowicz, T. L. (2012). Microhabitat association of *Hemimysis anomala* on fish spawning reefs in Grand Traverse Bay, Lake Michigan. *Journal of Great Lakes Research*, *38*, 32–36.

de Lafontaine, Y., Marty, J., & Despatie, S. P. (2012). Swarms of the Ponto-Caspian mysid *Hemimysis anomala* in Montreal Harbour, St. Lawrence River, Canada. *Journal of Great Lakes Research*, *38*, 25–31.

Dettmers, J. M., Janssen, J., Pientka, B., Fulford, R. S., & Jude, D. J. (2005). Evidence across multiple scales for offshore transport of yellow perch (*Perca flavescens*) larvae in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*, 2683–2693.

Elliott, J. M. (1971). *Some methods for the statistical analysis of samples of benthic invertebrates*. Freshwater Biological Association. Scientific Publication No. 25.

Foltz, J. W., & Norden, C. R. (1977). Seasonal changes in food consumption and energy content of smelt (*Osmerus mordax*) in Lake Michigan. *Transactions of the American Fisheries Society*, *106*, 230–234.

Geisthardt, E. J., Suedel, B. C., & Janssen, J. A. (2021). *Monitoring the Milwaukee Harbor Breakwater: An Engineering With Nature® (EWN) Demonstration Project. ERDC/EL TR-21-2*. U.S. Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/

Gerking, S. D. (1953). Evidence for the concepts of home range and territory in stream fishes. *Ecology*, *34*, 347–365.

Hobbs, R. J., Higgs, E. S., & Hall, C. (2013). *Novel ecosystems: Intervening in the new ecological world order*. John Wiley & Sons.

Houghton, C. J., & Janssen, J. (2015). Changes in age-0 yellow perch habitat and prey selection across a round goby invasion front. *Journal of Great Lakes Research*, *41*, 210–216.

Janssen, J. (1978). Feeding-behavior repertoire of the alewife, *Alosa pseudoharengus*, and the ciscoes *Coregonus hoyi* and *C. artedii*. *Journal of Fisheries Research Board of Canada*, *35*, 249–253.

Janssen, J., Berg, M., & Lozano, S. (2005). Submerged terra incognita: The abundant but unknown rocky zones. The Lake Michigan Ecosystem: Ecology, health and management. In T. Edsall, & M. Munawar (Eds.), *The Lake Michigan ecosystem: Ecology, health, and management* (pp. 113–139). Academic Publishing.

Janssen, J., & Brandt, S. B. (1980). Feeding ecology and vertical migration of adult alewives (*Alosa pseudoharengus*) in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*, 177–184.

Janssen, J., & Luebke, M. A. (2004). Preference for rocky habitat by age-0 yellow perch and alewives. *Journal of Great Lakes Research*, *30*, 93–99.

Janssen, J., & Quinn, J. (1985). Biota of the naturally rocky area of southwestern Lake Michigan with emphasis on potential fish prey. In F. M. Diltri (Ed.), *Artificial reefs: Marine and freshwater applications* (pp. 431–442). Lewis Publishers.

Ketelaars, H. A., Lambregts-van de Clundert, F. E., Carpentier, C. J., Wagenvoort, A. J., & Hoogenboezem, W. (1999). Ecological effects of the mass occurrence of the Ponto–Caspian invader, *Hemimysis anomala* GO Sars, 1907 (Crustacea: Mysidacea), in a freshwater storage reservoir in the Netherlands, with notes on its autecology and new records. *Hydrobiologia*, *394*, 233–248.

Kornis, M. S., & Janssen, J. (2011). Linking emergent midges to alewife (*Alosa pseudoharengus*) preference for rocky habitat in Lake Michigan littoral zones. *Journal of Great Lakes Research*, *37*, 561–566.

Madenjian, C. P., Wesley, J. K., Eggold, B. T., Gorenflo, T. K., Price, J., & Santucci, V. (2019). Introduction to the state of Lake Michigan in 2016. In C. P. Madenjian (Ed.), *The state of Lake Michigan in 2016*. Great Lakes Fishery Commission. http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf

Marris, E. (2009). Ragamuffin earth. *Nature*, *460*, 450–454.

Marsden, J. E., Casselman, J. M., Edsall, T. A., Elliott, R. F., Fitzsimons, J. D., Horns, W. H., Manny, B. A., McAughey, S. C., Sly, P. G., & Swanson, B. L. (1995). Lake trout spawning habitat in the Great Lakes—A review of current knowledge. *Journal of Great Lakes Research*, *21*, 487–497.

Mills, E. L., Leach, J. H., Carlton, J. T., & Secor, C. L. (1993). Exotic species in the Great Lakes: A history of biotic crises and anthropogenic introductions. *Journal of Great Lakes Research*, *19*(1), 1–54.

Quinn, J. P., & Janssen, J. (1989). Crayfish competition in southwestern Lake Michigan: A predator mediated bottleneck. *Journal of Freshwater Ecology*, *5*, 75–85.

Rastorgueff, P. A., Harmelin-Vivien, M., Richard, P., & Chevaldonné, P. (2011). Feeding strategies and resource partitioning mitigate the effects of oligotrophy for marine cave mysids. *Marine Ecology Progress Series*, *440*, 163–176.

Ray, W. J., & Corkum, L. D. (2001). Habitat and site affinity of the round goby. *Journal of Great Lakes Research*, *27*, 329–334.

Ricciardi, A., & MacIsaac, H. J. (2000). Recent mass invasion of the North American Great Lakes by Ponto–Caspian species. *Trends in Ecology and Evolution (Personal Edition)*, *15*, 62–65.

Riley, S. C., Binder, T. R., Tucker, T. R., Menzies, J., Eyles, N., Janssen, J., Muir, A. M., Esselman, P. C., Wattrus, N. J., & Krueger, C. C. (2017). Islands in the ice stream: Were spawning habitats for native salmonids in the Great Lakes created by paleo-ice streams? *Fish and Fisheries*, *18*, 347–359.

Riley, S. C., Binder, T. R., Wattrus, N. J., Faust, M. D., Janssen, J., Menzies, J., Marsden, J. E., Ebener, M. P., Bronte, C. R., He, J. X., & Tucker, T. R.

(2014). Lake trout in northern Lake Huron spawn on submerged drumlins. *Journal of Great Lakes Research*, *40*, 415–420.

Ross, S. T. (2013). *Ecology of North American freshwater fishes*. University of California Press.

Stone, R. B. (1974). A brief history of artificial reef activities in the United States, *Proceedings of an international conference on artificial reefs* (pp. 24–27). Texas A&M University. Sea Grant Rep. TAMU-SG-74-103.

Sturtevant, R. A., Mason, D. M., Rutherford, E. S., Elgin, A., Lower, E., & Martinez, F. (2019). Recent history of nonindigenous species in the Laurentian Great Lakes; An update to Mills et al., 1993 (25 years later). *Journal of Great Lakes Research*, *45*(6), 1011–1035.

Turschak, B. A., Bunnell, D., Czesny, S., Höök, T. O., Janssen, J., Warner, D., & Bootsma, H. A. (2014). Nearshore energy subsidies support Lake Michigan fishes and invertebrates following major changes in food web structure. *Ecology*, *95*, 1243–1252.

Vanderploeg, H. A., Nalepa, T. F., Jude, D. J., Mills, E. L., Holeck, K. T., Liebig, J. R., Grigorovich, I. A., & Ojavee, H. (2002). Dispersal and emerging ecological impacts of Ponto-Caspian species in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*, 1209–1228.

Zar, J. H. (2010). *Biostatistical analysis* (5th ed.). Prentice-Hall, Inc.