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# Lake trout spawning habitat suitability at two offshore reefs in Illinois waters of Lake Michigan

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ABSTRACT

In Illinois waters of Lake Michigan, Julian's and Waukegan reefs were once-productive offshore commercial fishing sites. Currently, both reefs are stocked and naturally reproduced lake trout aggregate at these reefs during the spawning season. Attempts to document natural reproduction of lake trout at deep-water spawning sites in southwestern Lake Michigan have been hampered, in part, by a lack of detailed information on suitable spawning habitat and imprecise placement of egg collection devices. We developed high-resolution substrate and bathymetric maps for Julian's and Waukegan reefs using geo-referenced bathymetry readings, sidescan sonar, and underwater video. Spawning activity was evaluated at suitable and unsuitable habitat using egg traps deployed during the 2009 and 2010 spawning seasons. Sidescan sonar data allowed identification of suitable substrate at Waukegan (1%) and Julian's (2%) reefs as well as previously undocumented Waukegan South Reef (6%). Small, discrete areas with suitable spawning habitat (substrate and slope) were found and in total constituted <1% of all hard surfaces mapped at both the Waukegan Reef complex and Julian's Reef. No eggs were collected either year, due in part to difficulty sampling small, localized patches of suitable spawning habitat and extensive coverage of *Dreissena* and *Cladophora* species. In the future, use of this high-resolution habitat data combined with more precise egg or fry sampling equipment will allow for a more comprehensive evaluation of natural reproduction at these once-productive offshore reefs.



## Introduction

Historically, lake trout *Salvelinus namaycush* was the dominant predator and one of the most valued game fish throughout the Great Lakes. Annual commercial harvest of native lake trout in Lake Michigan exceeded 5.0 million lb during 1900–1950 (Baldwin et al., 2009; Hudson and Ziegler, 2014) and was consistently higher per surface area than that of any other Great Lake (Holey et al., 1995). A combination of overfishing and sea lamprey *Petromyzon marinus* predation resulted in the extirpation of lake trout from Lake Michigan by the 1960s (Coble et al., 1990; Eshenroder et al., 1983; Hansen, 1999). Reintroduction efforts began in 1965 when hatchery-reared lake trout were introduced to Lake Michigan through extensive stocking efforts (Eshenroder et al., 1983; Holey et al., 1995). Despite on-going stocking, re-establishment of self-sustaining, naturally reproducing populations has been slow and met with limited success (Bronte et al., 2008; Eshenroder et al., 1995).

Numerous studies have investigated spawning aggregations, habitat suitability, and egg deposition of stocked lake trout at historical spawning grounds and man-made structures in an effort to ascertain factors which attracted native lake trout to spawning grounds (Edsall and Kennedy, 1995; Holey et al., 1995; Marsden and Janssen, 1997; Marsden et al., 1995; Marsden et al., 2005). Evaluation of historical spawning sites suggested native lake trout spawned at nearshore and offshore sites with depths ranging from 3 to at least 80 m (Brown et al., 1981; Goodyear et al., 1982). Stocked lake trout have reportedly spawned on man-made rock piles <5 m in diameter (Marsden et al., 1995) to natural reefs as large as several km$^2$ (Marsden et al., 2005). While the size, depth and substrate of sites used by lake trout for spawning varies by location, areas consisting of rubble (65–256 mm) and/or cobble (257–999 mm) with interstitial spaces at least 20 cm deep and slopes ranging from 15° to 60° are thought to provide optimal spawning habitat (Fitzsimons et al., 2003; Marsden et al., 1995).

In southwestern Lake Michigan, Julian's and Waukegan reefs, two Silurian bedrock reefs approximately 14 km east and 28 km southeast of Waukegan Harbor, IL, were historically productive commercial offshore fishing sites for lake trout during fall spawning (Collinson et al., 1979). Julian's Reef was one of the last known reefs in Lake Michigan to support spawning of native lake trout and is believed to have been a significant source of natural reproduction (Goodyear et al., 1982). In an effort to restore spawning populations, Julian's Reef has received annual stockings

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since 1981 (no lake trout were stocked during 1990, 2000, and 2007), while Waukegan Reef, with the exception of 1977 through 1979 and 1997, has remained unstocked (FWS/GLFC, 2010). Recent analysis of fall lake trout assessments indicated the presence of mature female and male lake trout on both reefs during the spawning season and that the proportion of unclipped (not of hatchery origin) lake trout has been increasing since the mid-2000s (Patterson et al., 2016). Thus, both of these offshore reefs could play an important role in the successful recovery of lake trout in Illinois waters of Lake Michigan by providing suitable spawning habitat.

Greater distances from shore, increased water depth, and harsh weather conditions during the spawning season make evaluation of deep-water lake trout spawning sites difficult. However, technological advances in mapping tools have increased data collection capabilities and enabled scientists to overcome these logistical challenges, while minimizing time spent sampling in suboptimal conditions. Sidescan sonar provides images of acoustic reflectivity from surficial features at the sediment-water interface. These images can be pieced together in adjacent positions to produce a continuous map of the seafloor (mosaicing) and substrate types are discriminated through differing backscatter (reflected acoustic energy) characteristics (Meadows et al., 2005). Bathymetric data make it possible to render a three-dimensional depiction of bottom relief and can be used to evaluate localized changes in slope that represent a crucial component of lake trout spawning habitat. Combining sidescan sonar and bathymetric surveys along with substrate validation through ground truthing efforts (i.e., underwater video survey or physical substrate collection) enables detailed identification and quantification of substrate type as well as an evaluation of slope and substrate complexity, which collectively make up key components of lake trout spawning habitat.

Portions of Julian's Reef have been mapped (Holm et al., 1987; Horns et al., 1991), and subsequently data from Horns et al. (1991) were used to evaluate potential lake trout spawning habitat (Edsall et al., 1996) prior to the establishment of *Dreissena* species. In a more recent report, Redman et al. (2012) developed substrate and bathymetry maps of Julian's and Waukegan reefs, but their interpretation of suitable lake trout spawning habitat was limited by spatial analysis which relied on the intersection of ideal slope and suitable substrate information at discrete points. The purpose of this current study is to present sidescan sonar, bathymetry, and underwater video data collected previously by Redman et al. (2012) following a more rigorous and comprehensive evaluation of suitable lake trout spawning habitat at Julian's and

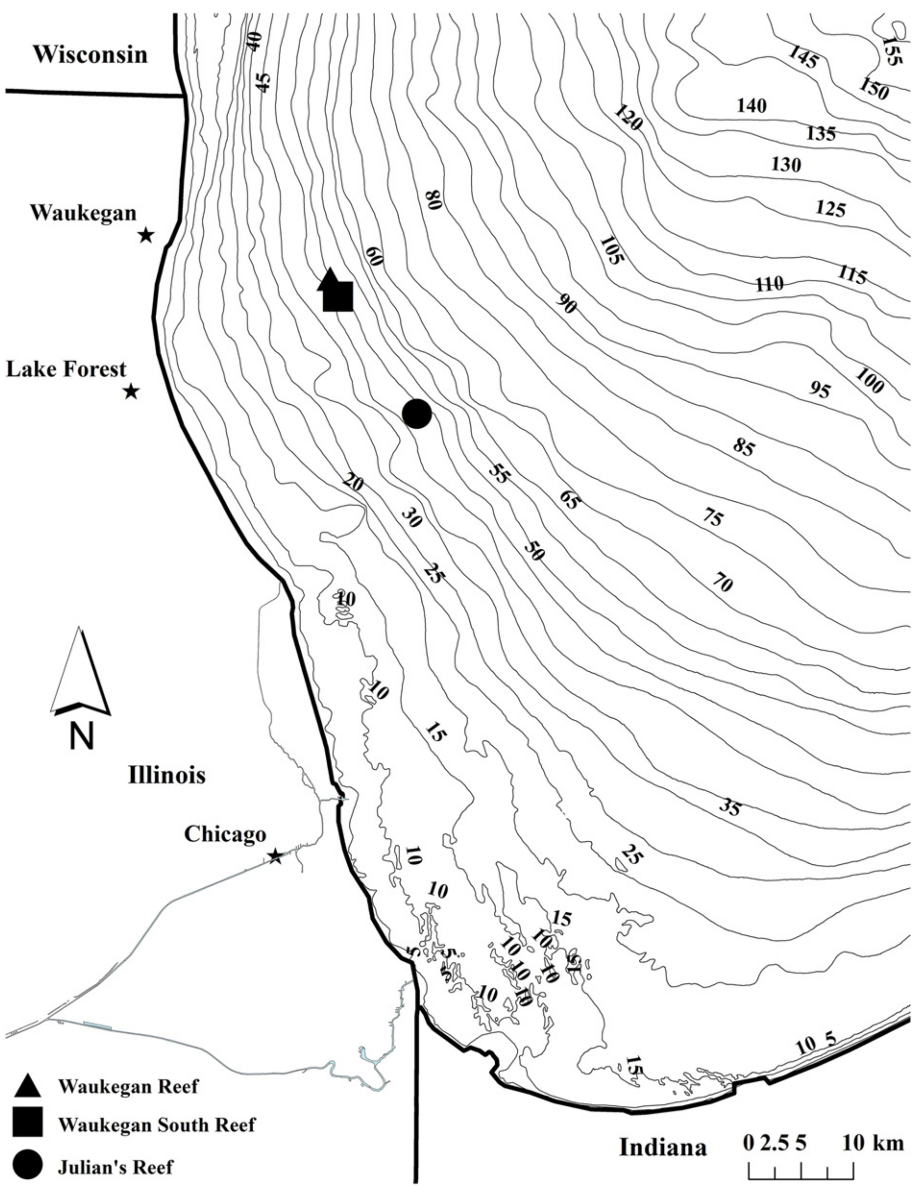


**Fig. 1.** Location of Julian's and Waukegan reefs and surrounding water depths (5 m contours) within the southern basin of Lake Michigan.

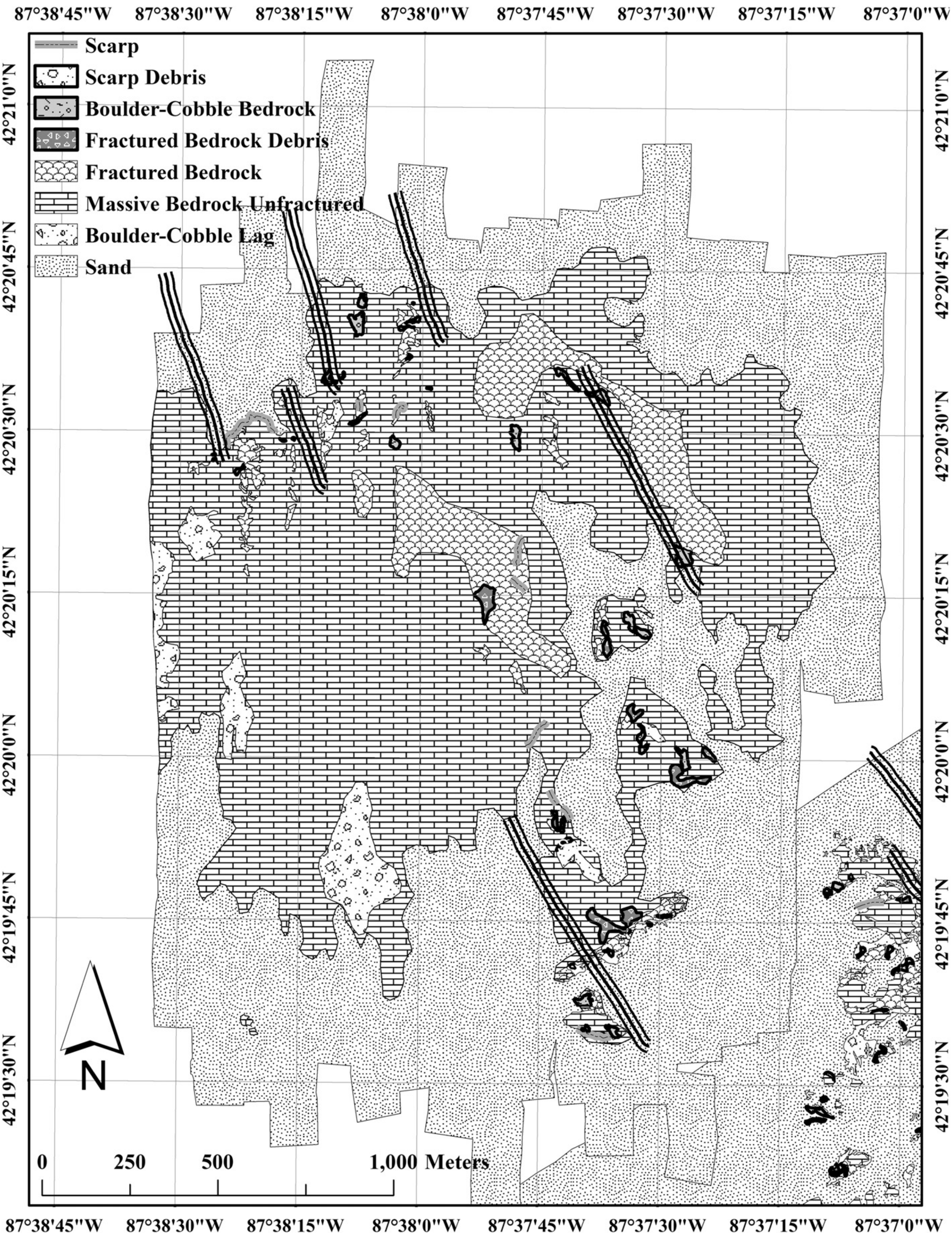


**Fig. 2.** Substrate map of Waukegan Reef highlighting substrate suitable for lake trout spawning with a black border (modified from Redman et al., 2012). Underwater video transects, used to validate substrate classification, are depicted by three parallel bold lines with the center line representing camera position.

Waukegan reefs. We also present results from deploying egg traps during the spawning season to empirically evaluate the suitability of lake trout spawning habitat at these once-productive reefs.

## Methods

Sidescan sonar, bathymetry, underwater video, and egg deposition data collected during 2009–2011 by Redman et al. (2012) were used to develop the modified substrate and newly interpreted bathymetric maps presented in this work. A L3-Klein System 3000 dual-frequency towfish and L3-Klein SonarPro™ software was used to collect sidescan sonar data at Waukegan and Julian's reefs (Fig. 1). A survey grade Trimble DSM 212H real-time differential DGPS (WAAS/EGNOS enabled) receiver operating at 1 Hz provided positional data that were automatically integrated into the sidescan sonar data using SonarPro™ software; positional accuracies of the DGPS were < 1 m. Initially, sidescan sonar data were collected along reconnaissance lines spaced approximately 500 m apart based, in part, on the location of prior reef surveys and fish sampling data for both Waukegan and Julian's reefs. Data were collected at a range setting of 150 m (width of sonar beam to each side of the towfish) resulting in a swath width (total width of lake bottom surveyed) of 300 m for each survey line. The towfish altitude was maintained at 15–20% of the water depth using an electrically driven hydrographic winch. Continuous real-time measurements of the amount of cable deployed were fed directly into the SonarPro™ software from a cable metering sheave to calculate towfish layback distances. Results of reconnaissance surveys at Waukegan Reef revealed the presence of multiple new bedrock features south of the originally defined survey area. These bedrock areas were smaller and more discretely distributed than the broad bedrock areas associated with Waukegan Reef to the north. Due to the potential of suitable spawning habitat within this previously undescribed region, the survey area was expanded and this region was designated Waukegan South Reef (Fig. 1). Collectively, Waukegan and Waukegan South reefs are referred to as the Waukegan Reef complex.

After initial reconnaissance, a more detailed survey grid was established over each reef with parallel survey lines spaced 112 m apart to facilitate mosaicing of higher resolution sidescan sonar data (75 m range, 150 m swath width, with a minimum of 25% overlap). Chesapeake Technologies SonarWizMap™ was used to produce geo-referenced mosaics from digital sidescan sonar data at each of the survey sites. The resulting mosaics were examined and areas exhibiting similar backscatter characteristics were identified. Substrates were then classified based on backscatter characteristics indicative of texture (i.e., grain size), composition, hardness, and observable surface features or structure (e.g., fractures in bedrock or sedimentary structures, such as ripples or dunes in sand). Areas with similar backscatter characteristics (i.e., inferred substrate types) were grouped into polygons that were then digitized from the geo-referenced sidescan mosaics and incorporated into a GIS database.

Underwater video data was collected along drift transects over all representative substrate types identified by sidescan sonar data to validate substrate composition at each reef. Prior to deploying the camera, the vessel was oriented to drift over the desired substrate and the camera was maintained 0.5–1 m from the lake bottom during data acquisition. The camera was connected by a 75-m cable marked at 1-m intervals to an on-board control panel that allowed real-time observation of the lake bottom during drift transects. The same survey grade Trimble DSM 212H real-time differential DGPD (WAAS/EGNOS enabled) receiver operating at 1 Hz was used to provide real-time positional data for the drift transects. Hard copies of the sidescan mosaics overlain with a detailed navigation grid were aboard the vessel for verification during underwater video data acquisition.

A single beam FURUNO echo sounder LS-6100 (200 kHz) with a thru-hull transducer and Standard Horizon CP180 GPS was used to collect bathymetry data during 2011. Data points included water depth measured to 0.1 m and vessel position (latitude and longitude from CP180) and were generated every 2–3 s along parallel survey lines spaced 100 m apart at all locations; vessel speed during bathymetry surveys was approximately 2.6 m/s. Time and budget did not allow completion of perpendicular survey lines for cross-checking over the entirety of each reef, but data were collected along shorter survey lines crisscrossing areas identified as suitable for lake trout spawning. Data from the nearest NOAA water level gauging stations (Calumet Harbor and Milwaukee) were used to correct bathymetric data for changing water surface elevations, because bathymetric surveys were conducted on multiple dates. Daily water level data were taken from both gaging stations to approximate water levels within the survey area for a given survey date.

During 2014, corrected bathymetry data were imported into ESRI ArcMap (ESRI, 2012) and interpolation procedures were performed using a Triangulated Irregular Network (TIN). The TIN procedure uses Delaunay triangulation with voronoi polygons to determine region of influence based on Euclidean distances between points and assumes the distances impose an “attraction” on neighbors (Burrough and McDonnell, 1998; Johnston et al., 2001). This interpolation is local (i.e., only surrounding points are included in analysis) and its predicted values were within the range of the data. Interpolation calculations were based on fitting a spherical variogram model (variance of the differences between field values at two locations) to the bathymetry data; a spherical model is shaped by a drastic increase and then an abrupt leveling off. Bathymetric data from all study sites were displayed using 1-m depth contours. Then, coverages of substrate deemed suitable for lake trout spawning were draped over the bathymetric surface and a TIN triangle (3D Analyst) was used to calculate slope (degrees) of potential habitat areas found at the study sites. The Identify tool within ArcMap was then used to locate areas where both substrate and slope, 15–60°, suitable for lake trout spawning were found (Fitzsimons et al., 2003; Marsden et al., 1995).

Eighty deep-water egg traps were constructed during 2009 following the design of Riley et al. (2010). Each egg trap consisted of a 48 cm diameter hoop of 6 mm galvanized steel. The body of each trap was composed of a cylindrical piece of 3 mm mesh that was cinched closed 40 cm below the frame and filled with 5 L of 5 cm plastic ‘bio barrels’ to

**Table 1**
Total area and percent area of substrates identified within the Waukegan Reef complex and Julian's Reef surveys. Substrates suitable for lake trout spawning are indicated with an asterisk.

| Substrate | Waukegan Reef (North) | | Waukegan South Reef | | Julian's Reef | |
|---|---|---|---|---|---|---|
| | Area ($m^2$) | Percent area | Area ($m^2$) | Percent area | Area ($m^2$) | Percent area |
| Scarp (linear feature) | 665 (m) | | 2,012 (m) | | 2,395 (m) | |
| Scarp debris* | na | na | 1,529 | 0.03 | na | na |
| Boulder-cobble bedrock* | 15,625 | 0.31 | 25,676 | 0.51 | 15,184 | 0.21 |
| Fractured bedrock debris* | 15,738 | 0.31 | 6,877 | 0.14 | 43,310 | 0.60 |
| Fractured bedrock | 261,506 | 5.15 | 92,234 | 1.84 | 3,281,246 | 45.10 |
| Massive bedrock unfractured | 2,163,778 | 42.62 | 306,428 | 6.12 | 94,822 | 1.30 |
| Boulder cobble lag | 116,646 | 2.30 | 136,458 | 2.73 | na | na |
| Sand | 2,503,348 | 49.31 | 4,437,643 | 88.63 | 3,841,540 | 52.80 |
| All substrates | 5,076,641 | 100 | 5,006,845 | 100 | 7,276,102 | 100 |

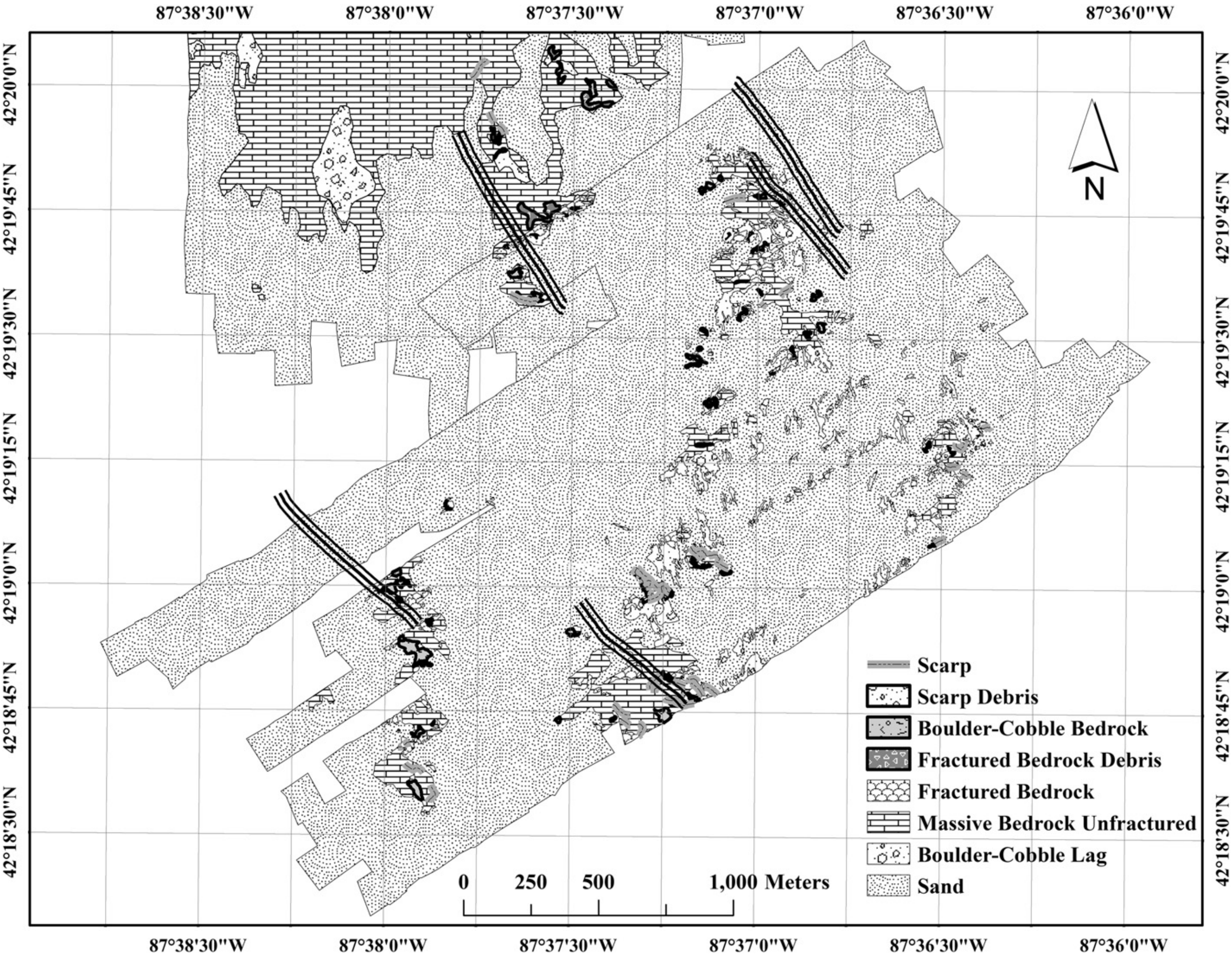


**Fig. 3.** Substrate map of Waukegan South Reef highlighting substrate suitable for lake trout spawning with a black border (modified from Redman et al., 2012). Underwater video transects are depicted by three parallel bold lines with the center line representing camera position.

provide structure, aid entrainment of eggs, and hinder consumption of eggs by predators able to penetrate the polyethylene mesh lid. Ten egg traps were linked using nylon rope with 2.4 m spacing between each trap to create a gang and four gangs were deployed at both the Waukegan Reef complex and Julian's Reef. At each reef, two gangs were deployed on substrate deemed suitable for lake trout spawning, while the other two gangs were deployed as controls on substrate deemed not suitable. Suitability of the substrate and selection of egg traps sites was based on interpretation of sidescan sonar data combined with historical fish sampling data from the Illinois Department of Natural Resources. Egg traps were deployed on October 20th and retrieved on November 4th, 2009. During 2010, egg traps were deployed at the same locations on October 4th and retrieved on November 2nd. Underwater video was collected post-deployment to confirm the placement of eggs traps on suitable substrate. After retrieval, egg traps were disassembled at the laboratory and examined for intact eggs and egg chorions.

## Results

### *Waukegan Reef complex*

Initial interpretation of sidescan sonar data at Waukegan Reef showed extensive sand areas and thin sands resting on smooth bedrock surfaces with intermittent exposures of massive and/or fractured bedrock exhibiting moderate relief. Total area of identified hard substrate, reef size, was 2,573,293 $m^2$ and constituted 51% of the total area mapped. More detailed analysis within the survey area showed that predominant substrate classes were sand (49%), massive bedrock (43%) and to a lesser extent exposed fractured bedrock (5%; Fig. 2). Potential lake trout spawning substrate at the Waukegan Reef included a complex pattern of boulder-cobble piles (average area 625 $m^2$) and fractured bedrock debris (average area 1749 $m^2$); collectively these substrates totaled to 31,363 $m^2$ (<3% of survey area; Table 1 and Fig. 2).

**Table 2**
Mean size, total area, and percent of each substrate type containing potential lake trout spawning habitat at the Waukegan Reef complex and Julian's Reef.

| Substrate | Mean habitat size ($m^2$) | Total habitat area ($m^2$) | Percent habitat |
|---|---|---|---|
| Waukegan | | | |
| Boulder-cobble | 922 | 9,218 | 58.99 |
| Fractured bedrock debris | 2,071 | 12,428 | 78.97 |
| Julian's | | | |
| Boulder-cobble | 1,253 | 7,519 | 49.52 |
| Fractured bedrock debris | 3,213 | 9,638 | 22.25 |

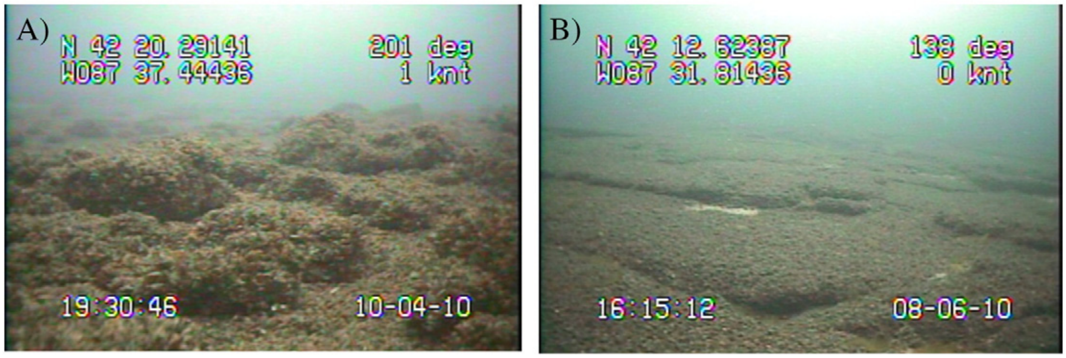


**Fig. 4.** Images from underwater video of boulder-cobble substrate at Waukegan Reef (A) and massive bedrock surfaces at Julian's Reef (B) with extensive *Dreissena* mussel colonization observed at both locations (taken from Redman et al., 2012).

Predominant substrate classes at the Waukegan South Reef survey area were sand (89%), and to a lesser extent massive bedrock (6%) and boulder-cobble lag deposits (3%; Table 1 and Fig. 3). Total area of identified hard substrates, reef size, was 569,202 $m^2$ and constituted 11% of the total area mapped. A portion of the sand deposits surrounding the eastern side of the Waukegan South Reef was

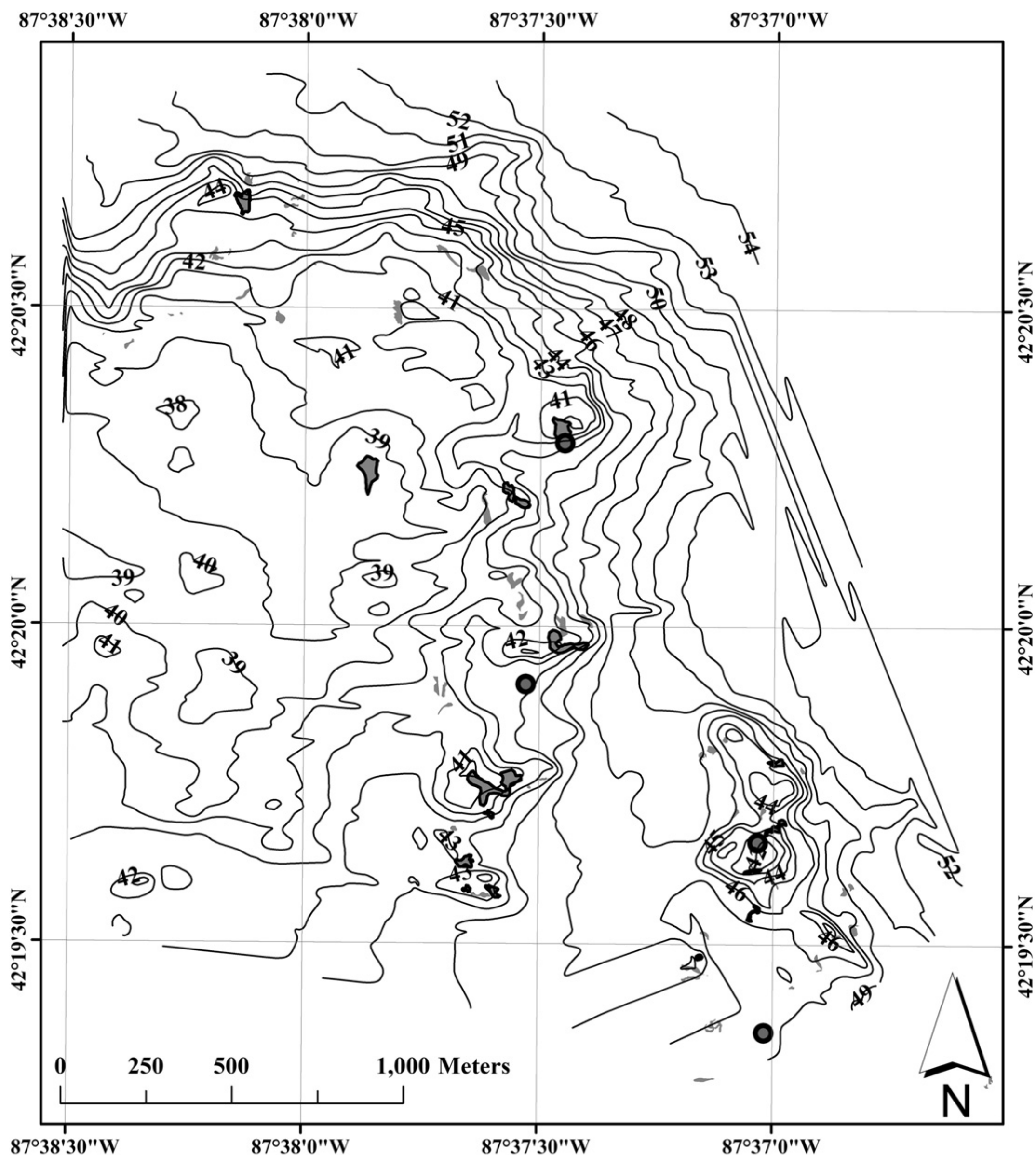


**Fig. 5.** Contour map (1 m) of the Waukegan Reef complex indicating areas containing suitable lake trout spawning habitat (substrate and slope) with a bold border and suitable substrates not containing suitable slope indicated in grey without a border (modified from Redman et al., 2012). Locations of egg trap sites (n = 4) are indicated with circles.

characterized by linear striping (see Redman et al., 2012 for location) and showed evidence of bedrock and/or glacial till beneath a veneer of sand. These deposits were interpreted as boulder-cobble lag deposits and were typically found adjacent to exposures of flat-lying massive bedrock and/or areas of exposed fractured bedrock. Associated with these bedrock substrates are bedrock scarps, areas of scarp debris, and boulder-cobble deposits overlying both massive and fractured bedrock surfaces (Fig. 3). Potential lake trout spawning substrate found at the Waukegan South Reef included scarp debris (mean area 255 $m^2$), fractured bedrock debris (mean area 264 $m^2$), and boulder-cobble piles (mean area 514 $m^2$); collectively, these substrates totaled to 34,081 $m^2$ (Table 2).

Underwater video footage was recorded along ten drift transects at the Waukegan Reef complex; the length of these transects averaged 588 m and a total of 5.88 line km of underwater video footage were archived (Figs. 2 and 3). Underwater video confirmed the presence of bedrock as well as coarse cobble-boulder substrate with characteristics suitable for use as lake trout spawning substrate at both Waukegan and Waukegan South reefs (Fig. 4a). Underwater video also revealed that virtually all of the coarse cobble-boulder substrate on both reefs is colonized by invasive *Dreissena* and *Cladophora* species, a green filamentous alga (Fig. 4a).

Water depths within the area surveyed at the Waukegan Reef complex ranged from 37.6 to 54.5 m, and substrate suitable for lake trout

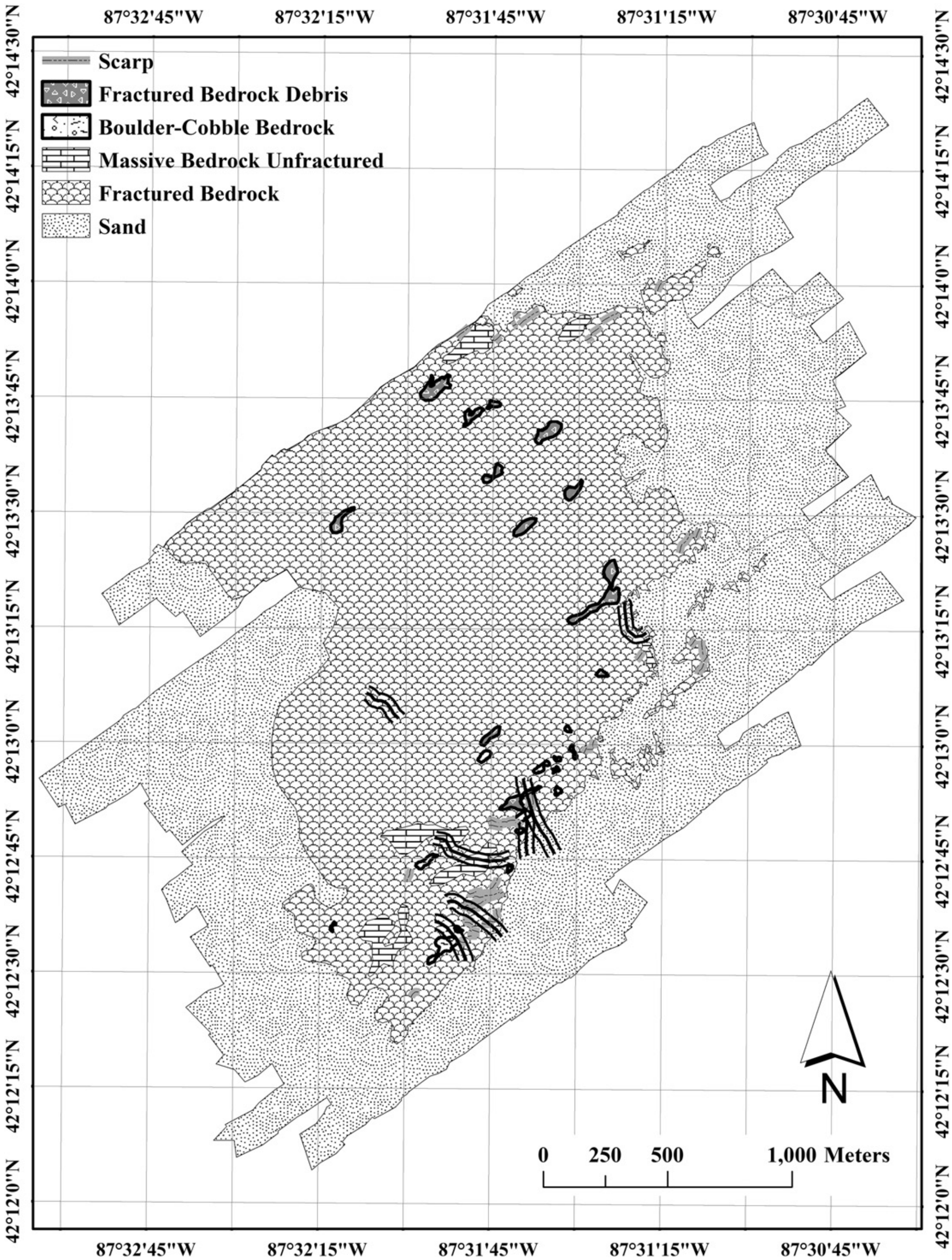


**Fig. 6.** Substrate map of Julian's Reef highlighting substrate suitable for lake trout spawning with a black border (modified from Redman et al., 2012). Underwater video transects are depicted by three parallel bold lines with the center line representing camera position.

spawning was found throughout this range (Fig. 5). Suitable substrate associated with ideal slope for lake trout spawning within the Waukegan Reef complex was composed of boulder-cobble piles and fractured bedrock debris and were primarily clustered in the southeastern portion of Waukegan Reef and the northern portion of Waukegan South Reef (Fig. 5). Fifty-nine percent of boulder-cobble piles (total area 9218 $m^2$) and 79% of fractured bedrock debris (12,428$m^2$) was interpreted to exhibit suitable slope, which ranged from 15 to 53° and occurred in depths of 38–46 m (Table 2). In total, this suitable spawning habitat made up 0.7% of all hard surfaces (21,646 $m^2$) mapped at the Waukegan Reef complex. No intact eggs or egg chorions were collected in gangs of egg traps placed at likely or unlikely spawning habitat either year. However, invasive quagga mussels *Dreissena bugensis* and round goby *Neogobius melanostomus* were collected during both years.

### *Julian's Reef*

Sidescan sonar data at Julian's Reef showed extensive sand areas overlying massive smooth bedrock surfaces with large exposures of fractured bedrock. Predominant substrate classes within the survey area were sand (53%), fractured bedrock (45%), and massive bedrock (1%; Table 1). Total area of identified hard substrates, reef size, was 3,434,562 $m^2$ and constituted 47% of the total area mapped. Within the expansive areas of sand surrounding Julian's Reef, a portion along the northeastern side of the reef was characterized by linear striping similar to that described within the eastern portion of the Waukegan South survey area (see Redman et al., 2012 for location). These areas were again interpreted to be a thin veneer of sand overlaying bedrock and/or glacial till; however, they generally consisted of finer grained materials than those found at Waukegan South Reef (i.e., smaller than boulder-cobble size). Numerous bedrock scarps, which form linear, bench-like features, were also found in the southeastern portion of Julian's Reef (Fig. 6).

Substrates suitable for lake trout spawning, boulder-cobble deposits and fractured bedrock debris, were found mostly scattered throughout the northern and southeastern portions of Julian's Reef and were much less prevalent than other substrates (<1%; Table 1 and Fig. 6). Boulder-cobble piles averaged 1085 $m^2$ and mean size of fractured bedrock debris fields was 3609 $m^2$; collectively these substrates totaled to 58,494 $m^2$ (Table 1). Fractured bedrock areas also have the potential to provide suitable lake trout spawning habitat, which may occur in relatively small and discrete patches scattered randomly across the reef.

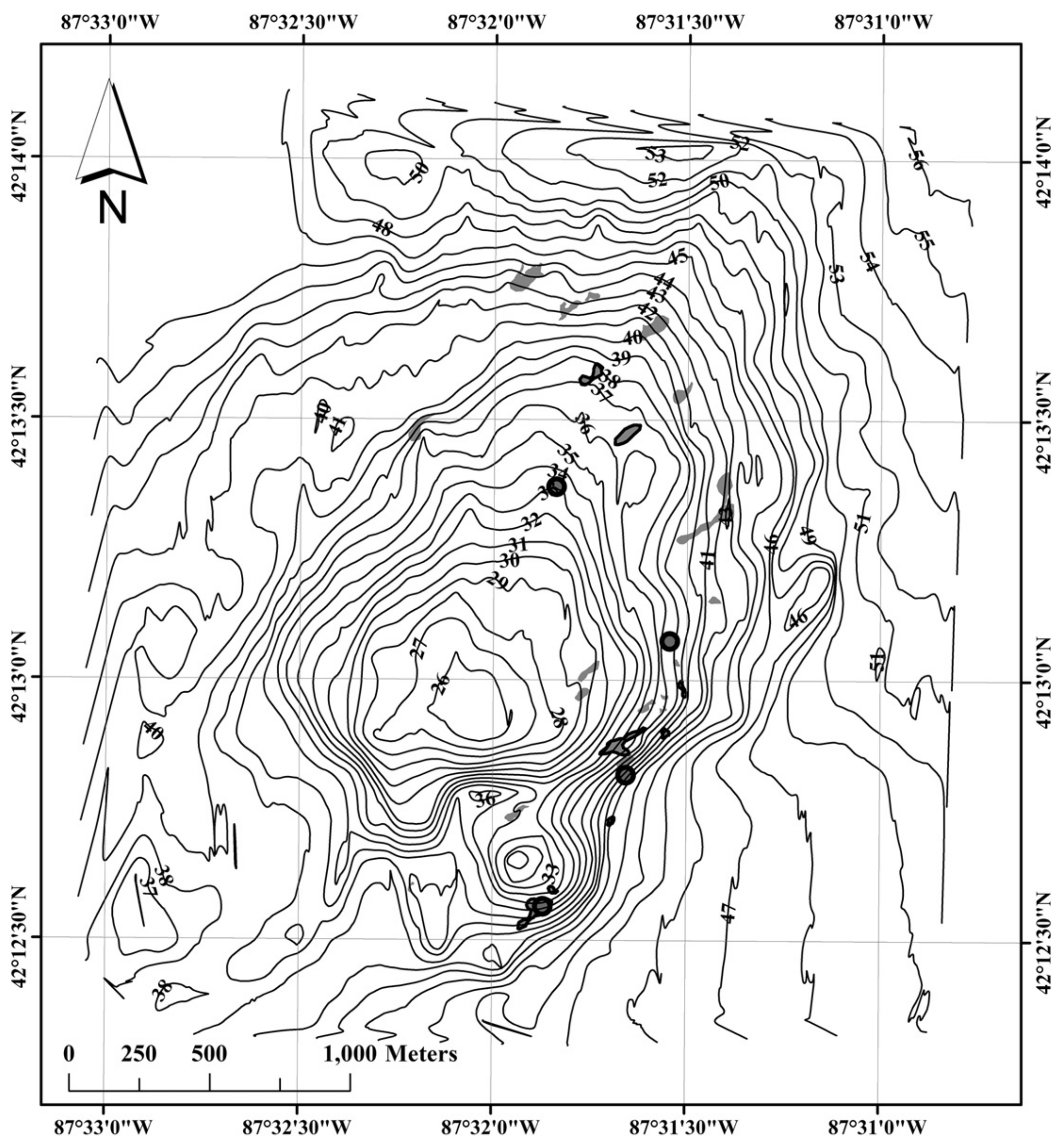


**Fig. 7.** Contour map (1 m) of Julian's Reef indicating areas containing suitable lake trout spawning habitat (substrate and slope) with a bold border and suitable substrates not containing suitable slope indicated in grey without a border (modified from Redman et al., 2012). Locations of egg trap sites (n = 4) are indicated with circles.

However, due to the structural complexity, sidescan sonar did not have the resolution to identify potential habitat areas within fractured bedrock.

Seven drift transects averaging 241 m in length were conducted at Julian's Reef, which totaled 1.68 line km of underwater video footage (Fig. 6). Underwater video confirmed the presence of bedrock as well as coarse cobble-boulder substrate with characteristics suitable for use as lake trout spawning habitat. Similar to that observed at the Waukegan Reef complex, underwater video also revealed extensive coverage of both *Dreissena* and *Cladophora* species (Fig. 4b).

Water depths within the Julian's Reef survey area ranged from 25.0 to 56.6 m and areas of suitable substrate were found throughout this depth range (Fig. 7). Suitable substrate associated with ideal slope were composed of boulder-cobble piles and fractured bedrock debris and were primarily found along the eastern portion of Julian's Reef (Fig. 7). The slope of these patches of potential lake trout spawning habitat ranged from 15 to 29° and were found in 34–42 m of water. Fifty percent of boulder-cobble piles (total area 7519 $m^2$) and 22% of fractured bedrock debris (9638 $m^2$) was interpreted to exhibit suitable slope (Table 2). In total, this designated suitable habitat made up 0.5% of all hard surfaces (17,157 $m^2$) mapped at Julian's Reef. Similar to that reported for the Waukegan Reef complex, no intact eggs or egg chorions were collected at Julian's Reef either year, but invasive quagga mussels and round goby were collected both years.

## Discussion

High-resolution substrate and bathymetric maps were created at both the Waukegan Reef complex and Julian's Reef using geo-referenced sidescan sonar, single beam sonar, and underwater video data. Substrates deemed suitable for spawning within the three survey areas were boulder-cobble piles, fractured bedrock debris, and scarp debris. Suitable spawning substrate made up 1% (31,363 $m^2$) of the hard/coarse substrates (excludes sand) found at Waukegan Reef and 6% (34,081 $m^2$) of that at Waukegan South Reef; collectively, suitable spawning habitat totaled 21,646 $m^2$ and was $<1\%$ of all hard substrates mapped at the Waukegan Reef complex. Thus, the newly described Waukegan South Reef contributed significantly to identification of spawning substrate in Illinois's offshore waters and was the only study site where scarp debris, which has been identified as spawning habitat for lake trout in Lake Erie, was found. At Julian's Reef, potential lake trout spawning substrate made up 2% (58,494 $m^2$) of the hard/coarse substrates while potential spawning habitat totaled 17,157 $m^2$ and again constituted $<1\%$ of all hard substrates mapped. Fractured bedrock areas found on Julian's Reef may also provide suitable lake trout spawning habitat that occur in relatively small and discrete patches located randomly across the reef; however, sidescan sonar data did not provide the resolution to identify these areas. It is possible that habitat within fractured bedrock areas could consist of relatively small and discrete patches located randomly across the reef. Overall, our results indicate that the Waukegan Reef complex provides a significant amount of potential lake trout spawning habitat and may contribute more to Illinois's historical spawning grounds than previously believed. These results highlight the significance that undiscovered or poorly mapped offshore reefs may play in providing suitable habitat for offshore species.

Underwater video confirmed the presence of fractured bedrock (Fig. 4b) as well as coarse cobble-boulder substrate with characteristics suitable for use as lake trout spawning habitat on both reefs (Fig. 4a). However, underwater video also revealed extensive coverage of *Dreissena* (*D. bugensis* found in egg traps) and *Cladophora* in up to 40 m of water (Fig. 4). Round goby, a known lake trout egg predator, was also frequently observed in video footage and collected in egg traps at both study sites. Spawning lake trout are reportedly attracted to clean substrate (little to no sedimentation) with deep interstitial spaces (Marsden et al., 1995); in southern Lake Michigan, lake trout egg deposition was 11 to 29 times greater at sites with unfouled cobble relative to locations heavily colonized by dreissenid mussels (Marsden and Chotkowski, 2001). A comparison of images from Edsall et al. (1996) of cobble-boulder piles on Julian's reef during the 1990s and those captured during this study illustrate the major alterations invasive species have had on offshore reefs. Currently, interstitial spaces, which are essential for lake trout egg development and survival, may be clogged with fine silt and pseudofeces from dreissenid mussels. Therefore, while suitable cobble-boulder piles and debris deposits were identified using sidescan sonar, the extent to which these substrates may be compromised by sedimentation and predation remains unknown.

Taken together, the small size of potential spawning habitat patches, subsequent difficulty targeting these discrete habitat patches with egg traps, and major habitat alterations by invasive species at least, in part, explain the lack of egg deposition documented in this study. These and other deep-water areas, which were once thought of as historical spawning grounds, may now provide limited habitat suitable for successful spawning and reproduction of lake trout. Claramunt et al. (2005) reported higher lake trout egg deposition in shallow water (1 m) despite availability of spawning habitat in deeper waters (up to 9 m) and suggested this shallow water habitat, which was relatively free of *Dreissena* species, may have a greater potential to contribute to spawning success than deeper water habitats. In southwestern Lake Michigan, exposed fractured bedrock areas and manmade structures within Illinois's nearshore waters may provide favorable spawning habitat for lake trout. However, the presence of round goby in nearshore areas of southwestern Lake Michigan (Sara Creque Illinois Natural History Survey, personal communication, 2016) and their impact as egg predators may significantly reduce egg survival in these areas.

Sidescan sonar was used to guide placement of egg traps over suitable substrate; however, the small size and patchy distribution of suitable substrate made precise deployment of egg traps difficult. Analysis of bathymetric data later confirmed deployment of egg traps on or near suitable slope and further truncated areas of suitable habitat (suitable substrate and slope; Figs. 5 and 7). While suitable spawning habitat comprised a relatively small proportion of our study area it is unlikely that lake trout spawning activity was limited by the quantity of available habitat. For example, lake trout eggs and fry were collected near Stony Island, Lake Ontario, in an area constituting $<10\%$ of the total reef area (Horns et al., 1989). Fitzsimons et al. (2003) noted that despite unidentifiable differences in slope or substrate size at egg trap locations in Lake Ontario, lake trout egg distribution among traps was not uniform. This suggests that lake trout are capable of identifying microhabitat that may not be readily identifiable through habitat evaluation alone. Given the small size of suitable habitat and high likelihood of microhabitat selection by late trout, it is possible that our sampling methodology was too coarse to accurately evaluate egg deposition. It also remains possible that, despite success in other studies, lake trout actively avoided egg traps as a result of the stark contrast with surrounding substrate (Horns et al., 1989). Precise sampling methods such as a tethered unmanned submersible have previously been used to collect lake trout eggs and fry at offshore reefs in Lake Michigan (Janssen et al., 2006). However, similar sampling at Julian's Reef was met with mixed results as deposited eggs were not observed, and areas sampled were of poor quality (Marsden and Janssen, 1997). Incorporating our high-resolution habitat data with sampling methods that allow for precise placement such as a remotely operated vehicle after egg deposition would limit search time, eliminate the possibility of net avoidance, and thus provide a better evaluation of natural reproduction at specific locations favorable for lake trout egg deposition.

Recent evidence suggests that efforts to develop naturally reproducing lake trout stocks have begun to bear fruit as the percentage of naturally reproduced lake trout collected at both Julian's and Waukegan reefs has continued to increase since the mid-2000s (Patterson et al., 2016). In Lake Huron, lake trout have been shown to exhibit high spawning site fidelity, ranging from 78% to 94% (Binder et al., 2016).

Therefore, it is likely that naturally spawned, sexually mature, lake trout collected at Julian's and Waukegan reefs originated at these locations. This project provided a more comprehensive habitat analysis of the first complete, detailed substrate and bathymetry data sets collected at both Julian's and Waukegan reefs by evaluating the status, quality, and quantity of potential lake trout spawning habitat. Incorporating these results into future endeavors will enable fine-scale sampling in an effort to document egg deposition and successful natural reproduction through fry collection. Given the extensive colonization of non-native species, further research is necessary to evaluate how habitat modifications as well as the presence of non-native species at offshore reefs influence lake trout spawning behavior, egg deposition, and egg and fry survival.

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