Great Lakes Fish and Wildlife Restoration Act
Final Report

Project Title: Evaluation of lake trout spawning reef suitability in Illinois waters of Lake Michigan

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Study Objectives:

Historically, lake trout *Salvelinus namaycush* was the dominant top predator in Lake Michigan and throughout the Great Lakes (Wells and McLain 1972; Eshenroder and Burnham-Curtis 1999). It was extirpated from Lake Michigan by the mid-1950s, due to a combination of commercial overfishing and sea lamprey *Petromyzon marinus* predation (Coble et al. 1990; Hansen 1999). With the advent of sea lamprey control, efforts to restore lake trout to Lake Michigan began in 1965, when stocking first took place (Holey et al. 1995). Because of its role as a native predator, management for sustainable, naturally reproducing lake trout stocks is a critical goal of the Great Lakes Fishery Commission (Eshenroder et al. 1995). Fish Community Objectives call for self-sustaining populations of lake trout that comprise 20 – 25% of the entire salmonine community, based on harvest (Eshenroder et al. 1995). However, efforts to develop a self-sustaining population of lake trout in Lake Michigan have been largely unsuccessful. Spawning aggregations of stocked lake trout are well documented (Holey et al. 1995; Marsden and Janssen 1997), fertilized eggs have been frequently found (Marsden and Chotkowski 2001; Fitzsimons et al. 2003; Marsden 1994), fry have been observed (Marsden and Chotkowski 2001), but only rarely has evidence of naturally produced lake trout been found (Holey et al. 1995).

Although a significant amount of research on lake trout spawning aggregations and habitat suitability in Lake Michigan has concentrated on the northern third of the lake (Dawson et al. 1997; Bronte et al. 2003; Fitzsimons et al. 2003), lake trout also congregate and spawn farther south in Lake Michigan, especially at offshore reefs. In Illinois waters, both Julian's reef and Waukegan reef were productive commercial fishing sites during fall (Collinson et al. 1979). More recently, gill net assessment data indicated that the number of adult spawners at Julian's reef and Waukegan reef is similar to that found at the mid-lake reefs where eggs and fry have recently been found (Dale Hanson, personal communication, 2011). However, no detailed maps of Julian's and Waukegan reefs exist and there is a lack of recent information on lake trout egg deposition rates at these sites. The only previous mapping of Waukegan reef was the hydrographic map compiled from 1946 USACE soundings. In addition, the current Lake Michigan GIS database lacks adequate information regarding habitat characteristics of the entire southwest portion of Lake Michigan.

In order to address these research needs, we established the following objectives for this project:

1) Develop high resolution bathymetric and substrate maps for Julian's and Waukegan reefs using geo-referenced sonar readings, sidescan sonar, and underwater video to update the Lake Michigan GIS.

2) Identify suitable spawning habitat for lake trout at Julian's and Waukegan reefs using the collected bathymetric and substrate data. Utilize this information to determine egg deposition sampling sites by September 2009.

3) Measure lake trout egg deposition with egg traps deployed during the 2009 and 2010 spawning seasons to empirically evaluate the suitability of spawning habitat as determined by bathymetry and substrate collection in objective 2.

Description of Tasks:

Task 1: Sidescan sonar surveys

Sidescan sonar provided images of acoustic reflectivity created by backscatter from surficial features and objects at the sediment-water interface. Reflected acoustic energy (backscatter) is received and processed by the tool in order to provide a continuous acoustic image or "map" of the bottom.

During 2009, sidescan sonar data were collected from two bedrock reefs off the Illinois Lake Michigan shoreline, Waukegan and Julian's reefs. A L3-Klein System 3000 dual-frequency towfish and L3-Klein SonarPro™ software were used to collect the sidescan sonar data (Figure 1). A Trimble DSM 212H real-time differential GPS (DGPS) receiver operating at 1 Hz provided navigational data that is automatically integrated into the sidescan sonar data by the SonarPro™ software. Positional accuracies are typically less than one meter. The software generates navigation waypoints and overlays that are displayed and integrated with MapTech digital electronic charts. Survey lines were plotted in advance of each survey and were used to generate waypoints for vessel navigation.

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 over both Waukegan and Julian's reefs. The reconnaissance 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. Based on the preliminary results from the reconnaissance surveys, a more detailed survey grid was established over each reef. Parallel survey lines were spaced at 112 m to facilitate mosaicking of the higher resolution sidescan sonar data (75 m range, 150 m swath width). The more detailed sidescan sonar data were then processed using Chesapeake Technologies SonarWizMap™ mosaicking software to remove the water column and generate georeferenced sidescan sonar mosaics.

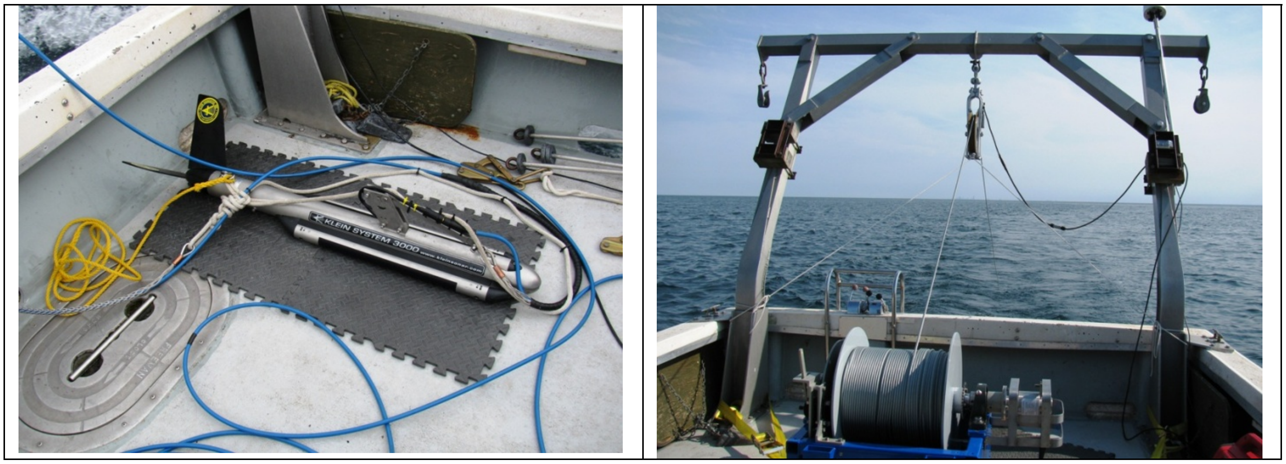


Figure 1. (a) L3-Klein sidescan sonar towfish with light-weight tow cable used for reconnaissance mapping over Waukegan and Julian's reefs. (b) Electrically driven hydrographic winch, armored coaxial cable, and digital cable counter used to deploy L3-Klein towfish during more extensive surveys over Waukegan and Julian's reefs. Equipment was deployed from the INHS *R/V SCULPIN*.

Waukegan Reef

The Illinois Department of Natural Resources (IDNR) has sampled several locations over the Waukegan reef for lake trout, and hypothesized that portions of this reef may contain substrate suitable for lake trout spawning due to large catches of spawning-stage lake trout in the fall. Virtually no detailed bathymetric data or historic substrate sampling/mapping data are available for Waukegan reef, so the lake trout spawning habitat potential was unknown for this reef complex. In the spring of 2009, a reconnaissance sidescan sonar survey was conducted over the reef; the location of survey lines was based on historical gill net sampling locations provided by the IDNR (Figures 2 and 3). During this survey, multiple new (unknown) bedrock areas were discovered south of the area originally associated with Waukegan reef. These bedrock areas are smaller and more discrete (patchy distribution) than the broad bedrock areas associated with Waukegan reef to the north. Based on the discovery of these previously unknown bedrock areas, the survey area was extended to include Waukegan South and a more detailed sidescan survey was performed during the summer of 2009 at Waukegan and Waukegan South, (collectively referred to as the Waukegan reef complex). Figures 2 and 3 illustrate the location of sidescan sonar survey lines and IDNR gill net sites over the Waukegan reef complex. More detailed information about the sidescan sonar surveys conducted over the Waukegan reef complex is summarized in Table 1.

Julian’s Reef

Julian’s reef was selected because prior IDNR surveys have documented spawning lake trout and the presence of lake trout eggs on substrates at Julian’s reef. In the spring of 2009, a reconnaissance sidescan sonar survey was conducted over the reef and a more detailed survey was performed during the summer of 2009 (Figures 2 and 3). The location of sidescan survey lines was based on historical gill net sampling locations provided by the IDNR and bathymetric data collected in the 1970’s and 1980’s by the Illinois State Geological Survey and IDNR. More detailed information about the sidescan sonar surveys conducted over Julian’s reef is summarized in Table 1. In total, 191 line km (96 line nm) of sidescan sonar data were collected at Julian’s and Waukegan reef during 2009, which covered an area greater than 17 km^2 of potential lakebed habitat.

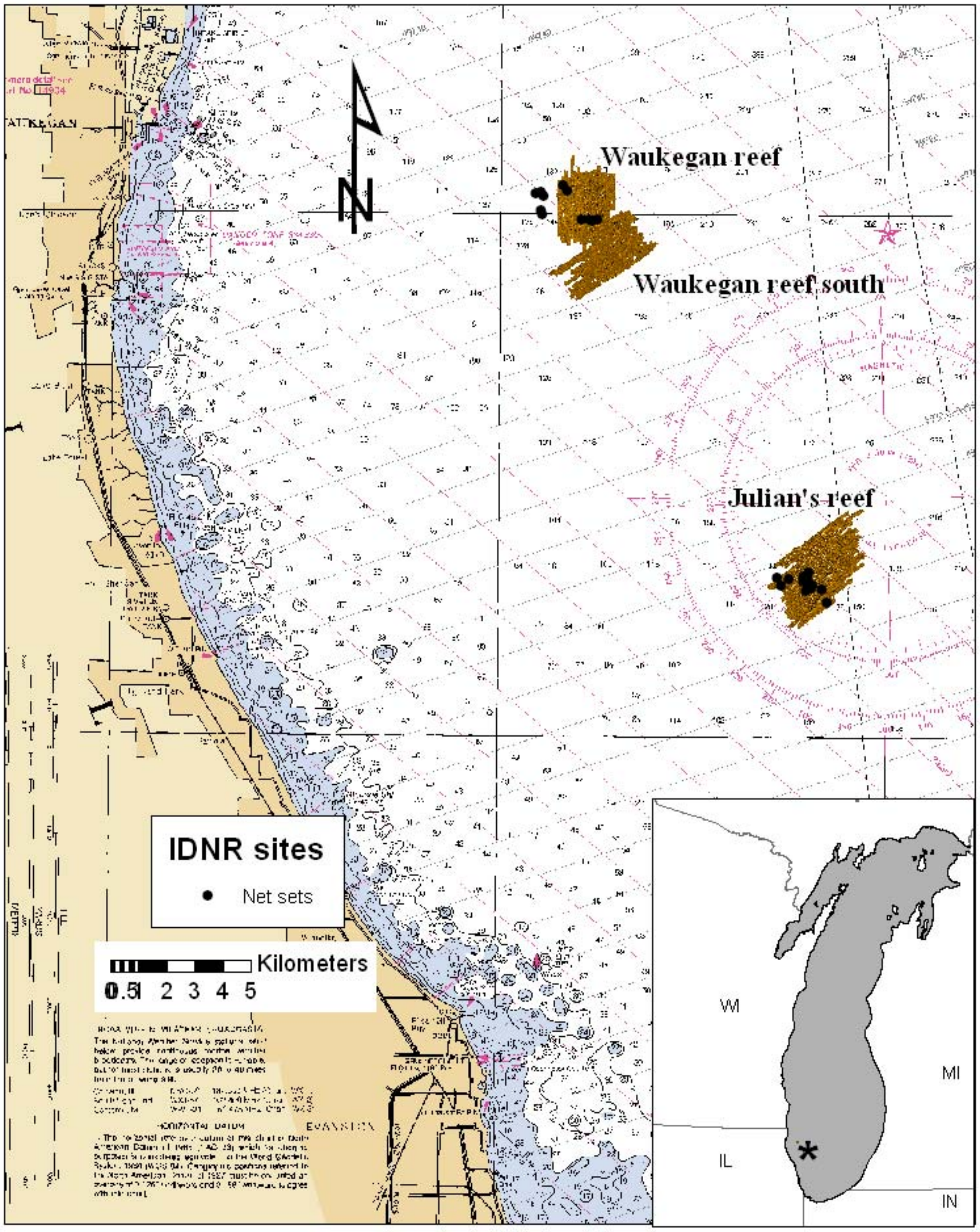


Figure 2. Location map showing survey areas over Waukegan and Julian's reefs in southwestern Lake Michigan.

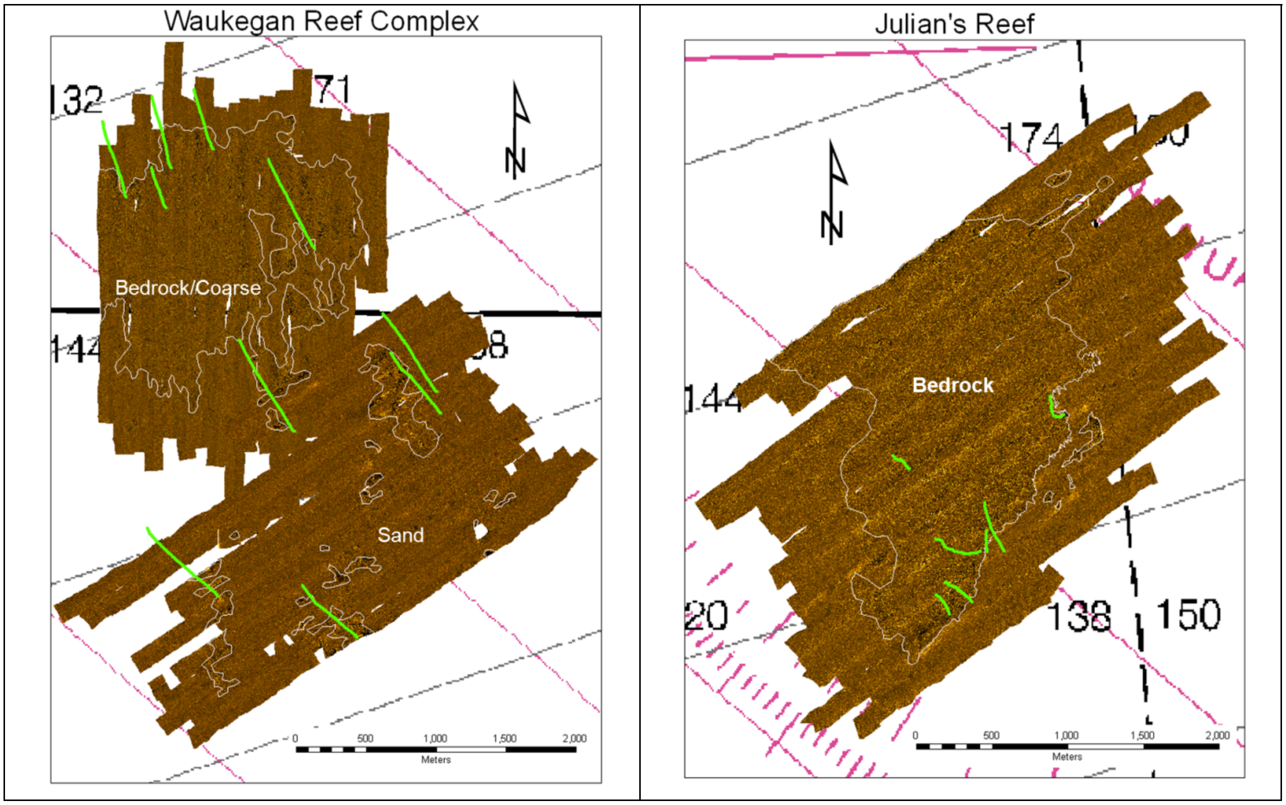


Figure 3. Sidescan sonar coverage and underwater video drift transects (green lines) at the Waukegan reef complex (left panel) and Julian's reef (right panel); the areas delineated by white lines are where bedrock and/or coarse cobble-boulder substrates were mapped on the lakebed.

Table 1. Summary of sidescan sonar survey data collected at the Waukegan reef complex and Julian's reef during this study.

Reef	Line km (nm)	Area (km^2)	Range (m)	Swath width (m)
Waukegan	20.9 (11.3)	Recon	150	300
Waukegan	40.4 (21.8)	5.00	75	150
Waukegan South	43.3 (23.4)	5.01	75	150
Waukegan Total	104.6 (56.5)	10.01		
Julian's	23.5 (5.7)	Recon	150	300
Julian's	62.4 (33.7)	7.23	75	150
Julian's Total	85.9 (39.4)	7.23		

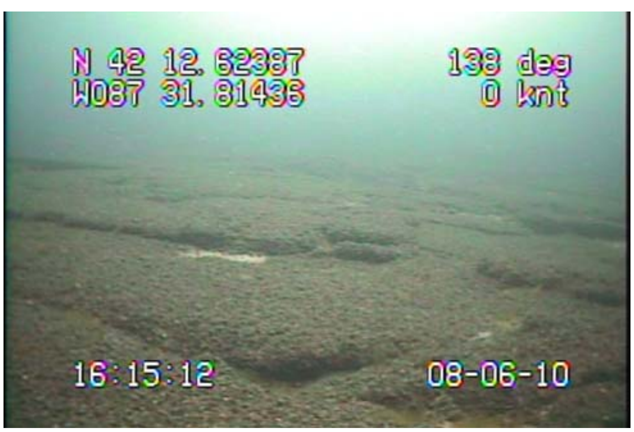
Task 2: Underwater video surveys

Underwater video provide highly-detailed images of the lake bottom which can be used to validate substrate composition and provide information on environmental characteristics such as presence of fine-grained sediments and encrustation by invasive mussels. We used drift transects to collect underwater video data at all study sites. Underwater video data were collected along ten drift transects at the Waukegan reef complex (Figure 3); the length of these transects averaged 588 m and a total of 5.88 line km (3.17 line nm) of underwater video data were collected (Table 2). Seven drift transects averaging 241 m in length were conducted at Julian's reef (Figure 3), which totaled 1.68 line km (0.91 line nm) of underwater video data (Table 2).

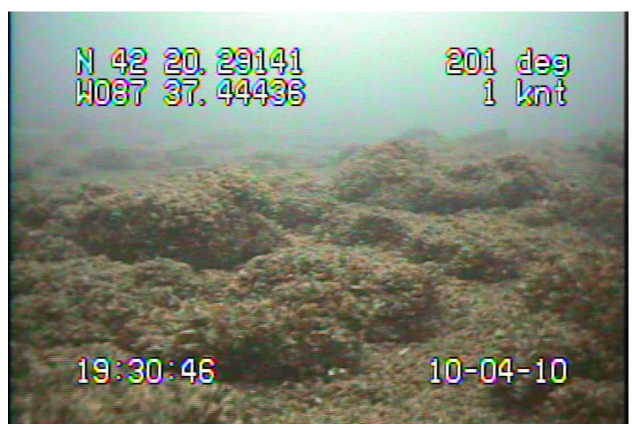
Table 2. Summary of underwater video data collected within the survey areas for the Waukegan reef complex and Julian's reef during this study.

Year	Reef	No. of Transects	Mean Length of Transects (m)	Total Line km	Total Line nm
2009	Waukegan	6	560	3.36	1.81
2009	Waukegan South	4	630	2.52	1.36
	Waukegan Total	10	588	5.88	3.17
2010	Julian's	7	241	1.68	0.91

The underwater video data confirmed the presence of bedrock (Figure 4a) as well as coarse cobble-boulder substrate with characteristics suitable for use as lake trout spawning habitat on both reefs (Figure 4b). The underwater video also revealed that virtually all of the coarse cobble-boulder substrate on both reefs is colonized by lithophyllic, invasive Dreissena spp. and Cladophora spp., a blue-green filamentous algae (Figures 4 and 5). Cladophora spp. was observed in water depths up to 40 m on Julian's reef.



a. Massive bedrock surfaces at Julian's reef.



b. Boulder-cobble near a lake trout egg trap site on Waukegan reef.

Figure 4. Images of lake bottom captured from underwater video data collected at Julian's reef and the Waukegan reef complex.

Figure 5. Extensive coverage of Dreissenids and Cladophora at Julian's reef.

Task 3: Spawning habitat analysis

Digital sidescan sonar data were processed and geo-referenced using Chesapeake Technologies SonarWizMap^{TM} mosaicking software to produce sidescan sonar mosaics at each of the survey sites. The resulting mosaics were examined and areas exhibiting similar backscatter characteristics were identified on the sidescan sonar mosaics and the waterfall displays. 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., substrate types) were grouped into polygons that were then digitized from the geo-referenced sidescan mosaics and incorporated into a GIS database. Prior work in Lake Michigan and comparable work in Lake Erie has shown that the acoustic response over similar substrate types is reasonably consistent between sites (Meadows et al. 2005). Moreover, ongoing work in the eastern basin of Lake Erie has demonstrated that it is possible to distinguish and map areas of increased or reduced habitat heterogeneity and/or potential lake trout spawning habitat (e.g. Biberhofer et al. 2010).

Based on similar work done in the eastern basin of Lake Erie (Biberhofer et al. 2010), two separate geodatabases were created for each survey site, one for substrate type and one for habitat structure. The approach used here is based on the concept that substrate provides information on the type and composition of lakebed materials, and that habitat structure provides information on the physical characteristics (or structure) at the lakebed-water interface, which is separate from but linked to substrate. It is the combination of substrate and habitat structure that is the primary factor that determines biological usage as habitat. Potential habitats were identified and mapped based on the integration of substrate and habitat structure polygons. Once potential habitats were identified and delineated within the GIS, an ESRI script was used to generate minimum bounding regions, which were then used to calculate the length and width of potential habitat areas (polygons) found within each survey area (see MBR; Frye 2008). Results of these analyses are presented below.

Waukegan Reef

Initial interpretation of the sidescan sonar data showed extensive sand areas and thin sands resting on smooth bedrock surfaces with intermittent exposures of massive and/or fractured bedrock exhibiting moderate relief. More detailed analysis within the survey area at Waukegan reef showed that predominate substrate classes were sand (49%), massive bedrock (43%) and to a lesser extent exposed fractured bedrock (5%; Figure 5). Areas interpreted as sand exhibit a rough acoustic (rippled) texture that may be covered locally by scattered dreissenid shell debris and a thin veneer of flocculent mud and/or pseudofeces. The Waukegan reef survey area also contains a complex pattern of boulder-cobble piles, fractured bedrock debris, and boulder-cobble lag deposits, (<3%; Table 3 and Figure 5). Potential lake trout spawning habitat areas found at Waukegan reef include boulder-cobble piles (average area 625 m^2), and fractured bedrock debris (1749 m^2; Table 4); collectively these substrates totaled to 31,363 m^2. Analysis of individual substrate polygons revealed that potential habitat areas suitable for spawning were typically less than 80 m in length and 60 m in width (Figure 6).

Table 3. Summary of habitat and substrate assessments using sidescan sonar within the survey area for Waukegan reef (northern portion). An asterisk is used to identify substrates determined to be potential lake trout habitat.

Substrate	Area (m^2)	Percent Area
Scarp (linear feature)	665(m)	
Boulder-cobble bedrock*	15625	0.31
Fractured bedrock debris*	15738	0.31
Boulder cobble lag	116646	2.30
Fractured bedrock	261506	5.15
Massive bedrock	2163778	42.62
Sand	2503348	49.31

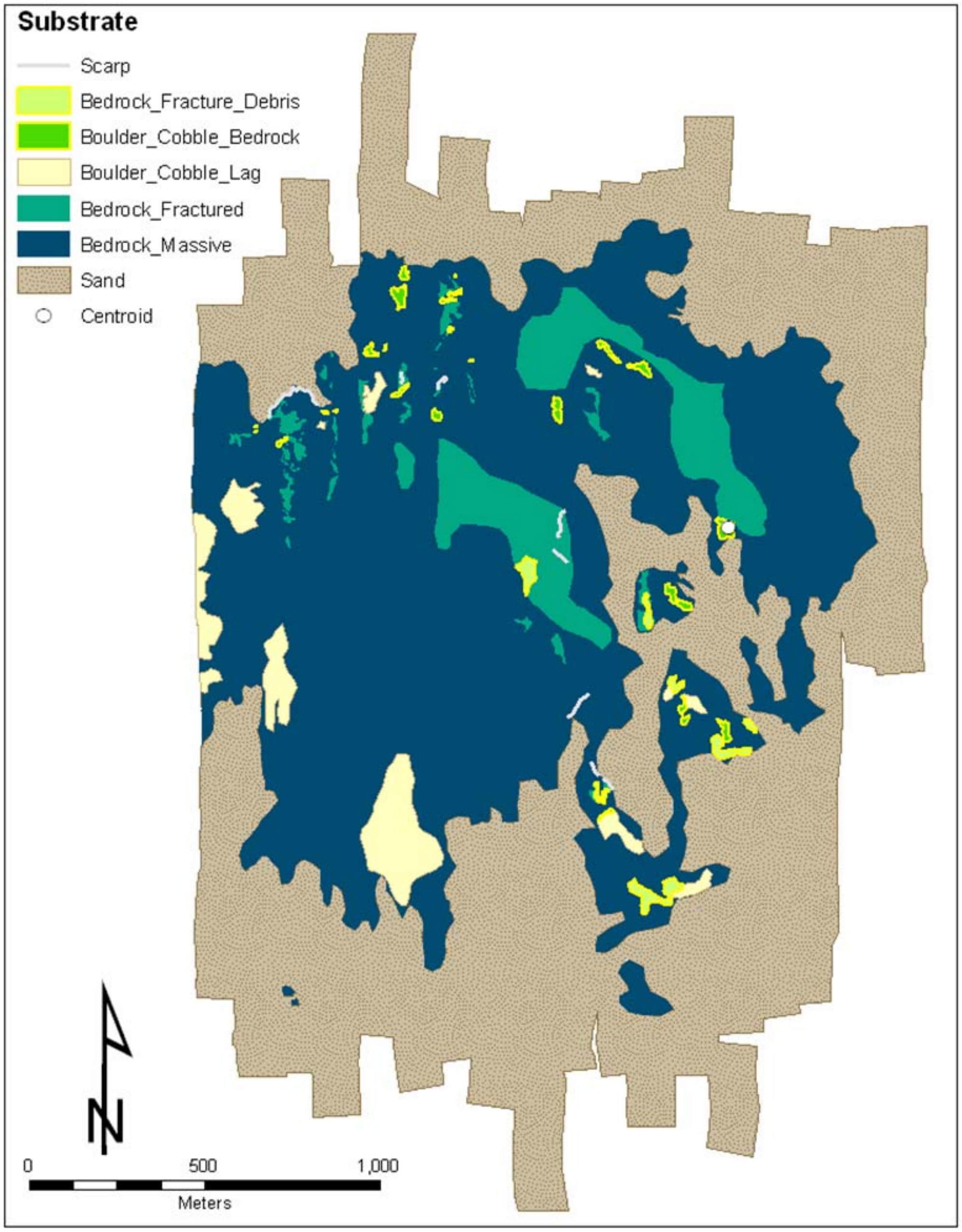


Figure 5. Substrate and habitat interpretations from sidescan surveys for Waukegan reef (northern portion) located within Illinois waters of Lake Michigan. Potential lake trout spawning habitat is outlined in yellow and the centroid of the egg trap site targeted during the 2009 and 2010 lake trout spawning seasons is depicted with a white circle.

Table 4. Average size of potential lake trout spawning habitat at the Waukegan reef complex and Julian's reefs.

Substrate	Area (m^2)	Length (m)	Width (m)
Waukegan			
Boulder-cobble	625	44	20
Fractured bedrock debris	1749	81	41
Waukegan South			
Boulder-cobble	514	37	18
Fractured bedrock debris	264	32	13
Scarp debris	255	38	18
Julian's			
Boulder-cobble	1085	55	26
Fractured bedrock debris	3609	126	53

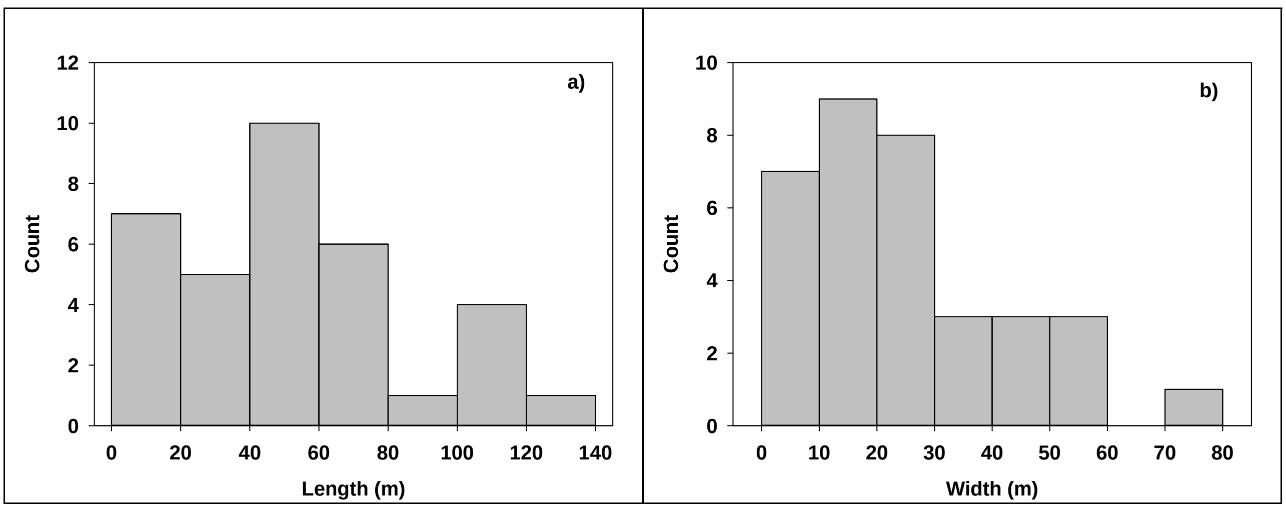


Figure 6 Frequency distribution of potential lake trout habitat by feature a) length and b) width derived from minimum bounding regions at Waukegan reef.

<u>Waukegan South Reef</u>

Initial interpretation of the sidescan sonar data showed extensive areas of sand mixed with smaller areas of bedrock and coarse-grained cobble-boulder deposits. More detailed analysis showed that the predominate substrate classes within the survey area for Waukegan South reef were sand (89%), and to a lesser extent massive bedrock (6%) and boulder-cobble lag deposits (3%;Table 5 and Figure 7). Areas interpreted as sand exhibit a rough acoustic (rippled) texture that may be covered locally by scattered dreissenid shell debris and a thin veneer of flocculent mud and/or pseudofeces. Some of the sand deposits surrounding the eastern portion of the Waukegan South survey area are characterized by linear striping and show evidence of bedrock and/or glacial till showing through a thin veneer of sand. These deposits have been interpreted as boulder-cobble lag deposits. These deposits are typically found adjacent to exposures of flat-lying massive bedrock and/or areas of exposed fracture bedrock within the Waukegan South survey area. Associated with these bedrock substrates are bedrock scarps, areas of scarp debris and boulder-cobble deposits overlying both massive and fractured bedrock surfaces (Figures 7 and 8). Examples of backscatter characteristics and interpreted substrates found within the study survey areas are illustrated in Figure 9. Potential habitat areas found at Waukegan South include scarp debris (average area 255 m^2), fractured bedrock debris (264 m^2), and boulder-cobble piles (514 m^2; Table 5); collectively, these substrates totaled to 34,081 m^2. Analysis of individual substrate polygons revealed that potential habitat areas suitable for use as spawning habitat were typically less than 70 m in length and 30 m in width (Figure 10).

Table 5. Summary of habitat and substrate assessments using sidescan sonar within the survey area for Waukegan South reef. An asterisk is used to identify substrates determined to be potential lake trout habitat.

Substrate	Area (m2)	Percent Area
Scarp	2012(m)	
Scarp debris*	1529	0.03
Fractured bedrock debris*	6877	0.14
Boulder cobble bedrock*	25676	0.51
Fractured bedrock	92234	1.84
Boulder-cobble lag	136458	2.73
Massive bedrock	306428	6.12
Medium coarse sand	4437643	88.63

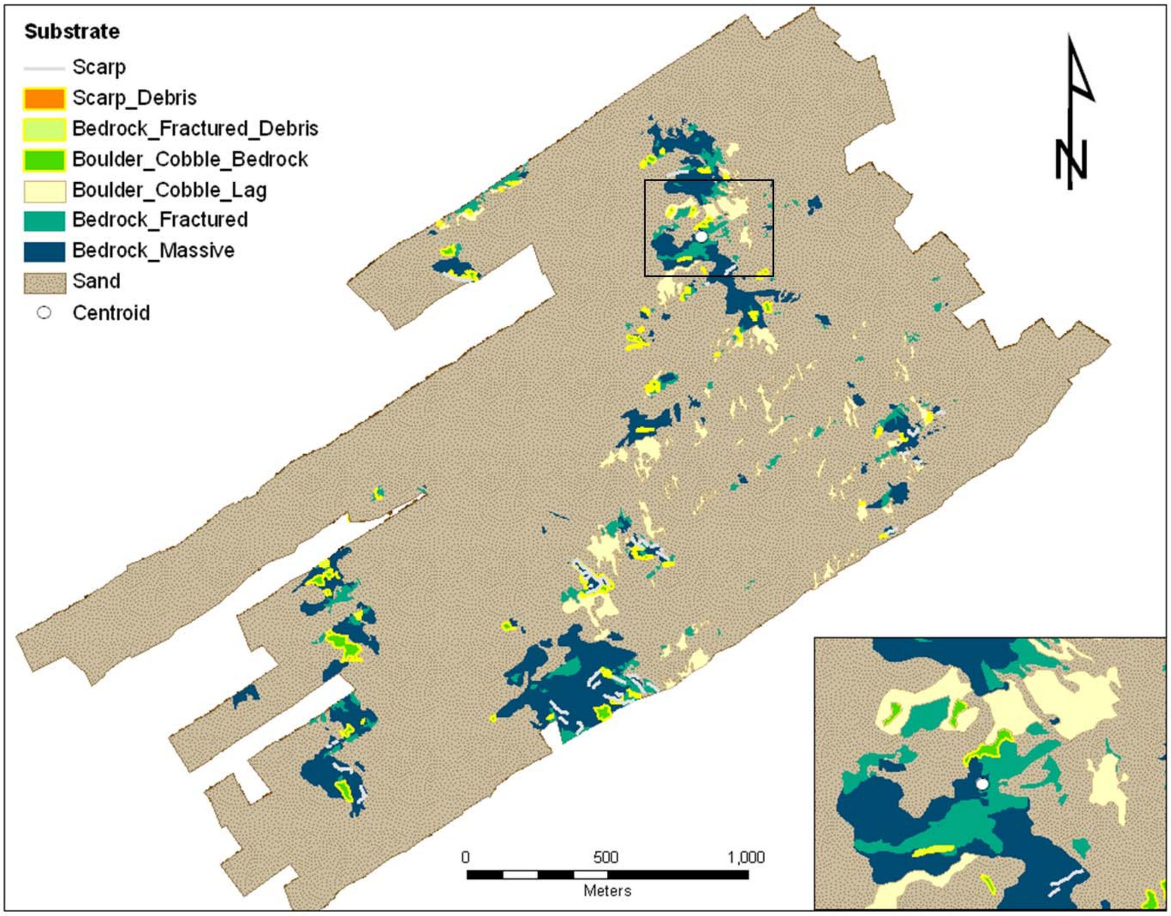


Figure 7. Substrate and habitat interpretations from sidescan surveys for Waukegan South reef located within Illinois waters of Lake Michigan; potential lake trout spawning habitat is outlined in yellow. The inset map (lower right corner) represents a close-up of an area of fractured bedrock that was targeted with deep-water egg traps during the 2009 and 2010 lake trout spawning seasons. The portion of the survey area that appears within the inset map is outlined with a black square, and the centroid of the egg trap site is depicted with a white circle.

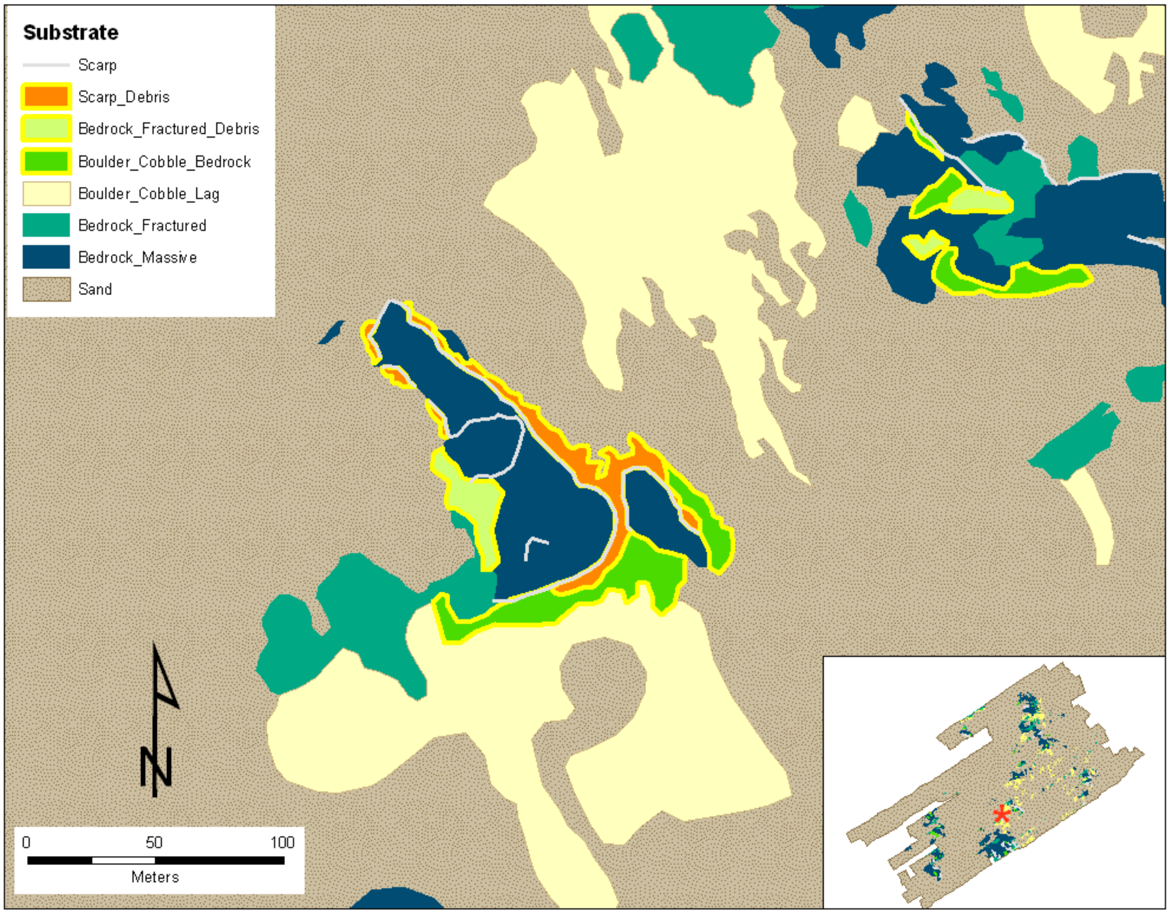


Figure 8. Map illustrating the presence of debris along a large bedrock scarp found within the southern portion of the Waukegan South reef survey area.

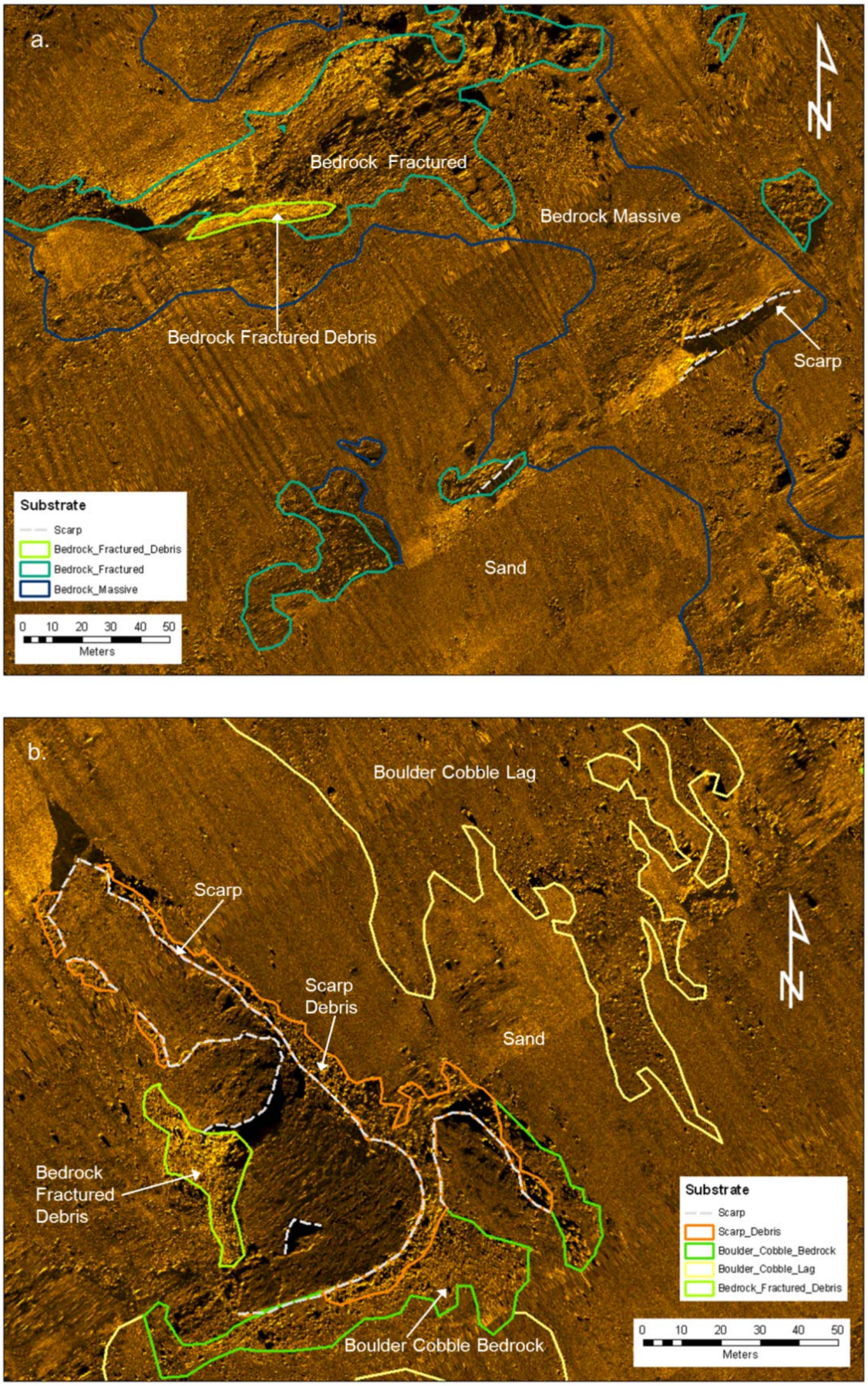


Figure 9. Sidescan sonar images illustrating the range of substrate types mapped on the Waukegan reef complex and Julian's reef in Illinois waters of Lake Michigan.

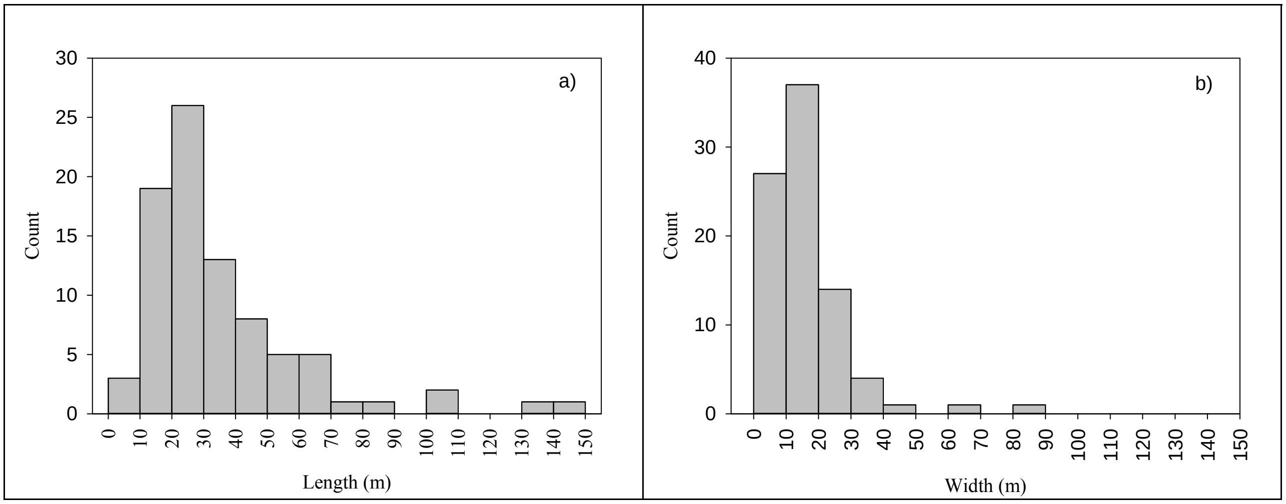


Figure 10. Frequency distribution of potential lake trout habitat by feature a) length and b) width derived from minimum bouding regions at Waukegan South reef.

Julian's Reef

Initial interpretation of the sidescan sonar data showed extensive sand areas overlying massive smooth bedrock surfaces with extensive exposures of fractured bedrock. More detailed analysis showed that the predominate substrate classes within the survey area at Julian's reef were fractured bedrock (45%), sand with patchy dunes (43%), areas of striped sand (10%), and to a lesser extent massive bedrock (1%). Areas of striped sand are interpreted to be a thin veneer of sand overlying bedrock and/or glacial till similar to that described within the eastern portion of the Waukegan South survey area. However, these areas were generally more fine grained (i.e. less boulder-cobble size material) than at the Waukegan South survey area. Areas interpreted as sand exhibit a rough acoustic (rippled) texture that may be covered locally by scattered dreissenid shell debris and a thin veneer of flocculent mud and/or pseudofeces. Julian's reef also contains boulder-cobble deposits and fractured bedrock debris, but these substrates were much less prevalent (<1%; Table 6 and Figure 11). The southeastern portion of Julian's reef is interesting because it not only contains scattered areas of coarse-grain substrate suitable for lake trout spawning (boulder-cobble and bedrock debris deposits), but is also characterized by numerous bedrock scarps that form linear, bench-like features (Figure 12). Edsall et al. (1996) also described extensive bedrock with rubble substrate and linear bedrock ridges within the southeastern portion of Julian's reef. Potential habitat areas found at Julian's reef include boulder-cobble piles (average area 1085 m^2) and fractured bedrock debris fields (3609 m^2;Table 6); collectively these substrates totaled to 58,494 m^2. Analysis of individual substrate polygons revealed that potential areas suitable for spawning were typically less than 150 m in length and 60 m in width (Figure 13). Fractured bedrock areas also have the potential to provide suitable lake trout spawning habitat. However, due to the structural complexity associated with fractured bedrock, the sidescan sonar data does not have the resolution to identify potential habitat areas within fractured bedrock. It is anticipated that potential habitat areas within the larger extent of fractured bedrock at Julian's reef would consist of relatively small and discrete patches scattered randomly across the reef.

Table 6. Summary of habitat and substrate assessments using sidescan sonar within the survey area for Julian's reef. An asterisk is used to identify substrates determined to be potential lake trout habitat.

Substrate	Area (m^2)	Percent Area
Scarp (linear feature)	2395(m)	
Boulder-cobble bedrock*	15184	0.21
Fractured bedrock debris*	43310	0.60
Massive bedrock	94822	1.30
Medium-coarse striped sand	743138	10.21
Medium-coarse sand & patchy dunes	3098402	42.58
Fractured bedrock	3281246	45.10

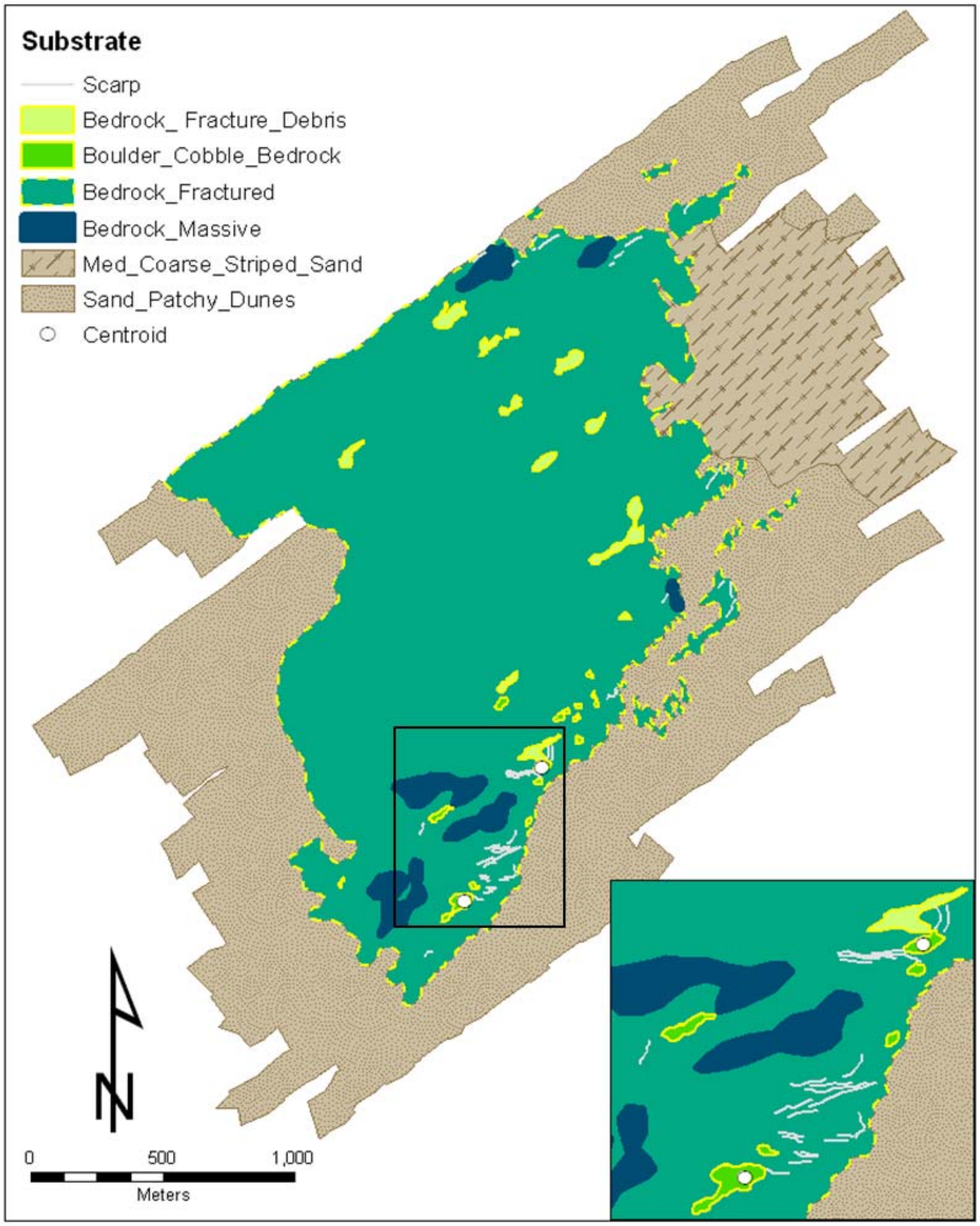


Figure 11. Substrate and habitat interpretations from sidescan surveys for Julian's reef located within Illinois waters of Lake Michigan; potential lake trout spawning habitat is outlined in yellow. The inset map (lower right corner) represents a close-up of two areas of boulder-cobble that were targeted with deep-water egg traps during the 2009 and 2010 lake trout spawning seasons. The portion of the survey area that appears within the inset map is outlined with a black square and the centroid of the egg trap sites are depicted with white circles.

Figure 12. Example of a bedrock scarp that form the linear, bench-like features within the southeastern portion of Julian's reef.

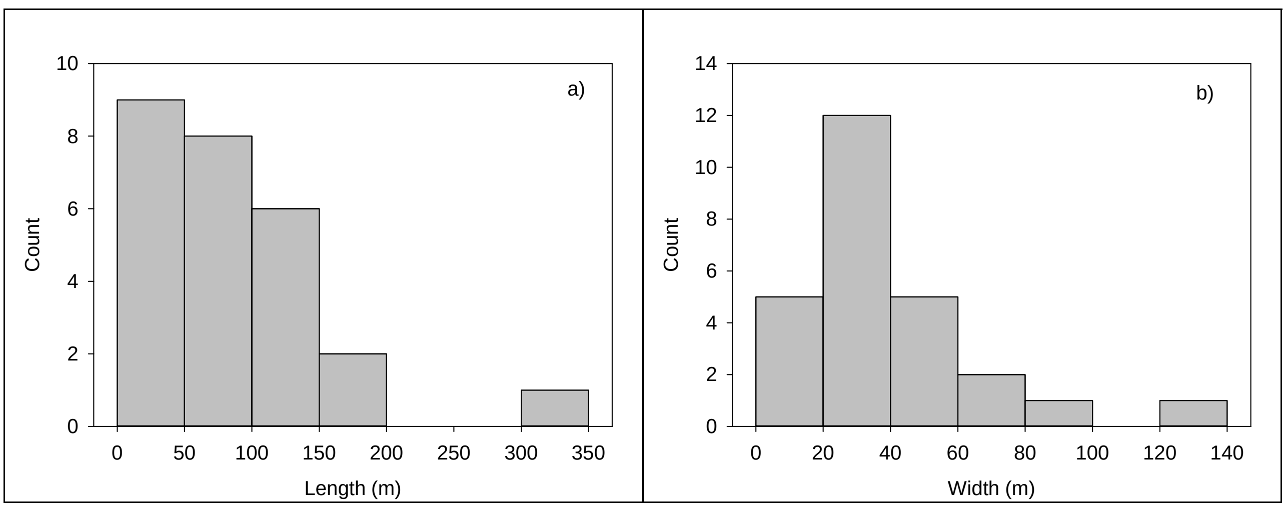


Figure 13. Frequency distribution of potential lake trout habitat by feature a) length and b) width derived from minimum bouding regions at Julian's reef.

Task 4: Bathymetric surveys

During 2011, bathymetry data was collected at both the Waukegan reef complex and Julian's reef. A single beam FURUNO echo sounder LS-6100 (200 kHz) with a thru-hull transducer and Standard Horizon chart plotter (CP180) were used to collect bathymetry data. Data points included water depth (0.1 m) and vessel position (in the form of latitude and longitude) and were produced every 2-3 seconds. Vessel speed during bathymetry surveys was approximately 2.6 m/s and allowed collection of a data point every 5.2-7.8 m along a survey line. Survey lines were plotted in advance of each cruise and used to generate waypoints for vessel navigation. Data was collected along a set of parallel survey lines spaced approximately 100 m apart at all survey sites.

The bathymetry system allowed real-time display of data which aided vessel navigation and allowed preliminary assessment of the data (Figure 15). Since bathymetric surveys were conducted on multiple dates, data from the nearest NOAA water level gauging stations (Calumet Harbor and Milwaukee) was used to correct bathymetric data for changing water surface elevations (relative to chart datum; 176.02 m). Daily water level data taken from both gauging stations (http://www.great-lakes.net/envt/water/levels/levels-cur/michwlc.html) was used to approximate water levels within the survey area for a given survey date. The extent of the bathymetry surveys conducted over both reefs and water level data for each sampling event are summarized in Table 7.

Table 7. Summary of bathymetry surveys conducted at the Waukegan reef complex and Julian's reef during 2011 as well as average daily water levels at the nearest gauge stations.

Reef	Survey Dates	Line km (nm)	Daily water level (m)			Δ from chart datum
			Calumet	Milwaukee	Mean	
Waukegan	July 7	40.0 (21.6)	176.321	176.300	176.311	0.290
Waukegan South	Aug. 1	6.0 (3.2)	176.282	176.272	176.277	0.257
Waukegan Total		46.0 (24.8)				
Julian's (south)	Aug. 30	55.0 (29.7)	176.209	176.211	176.210	0.190
Julian's (north)	Oct. 4	24.0 (13.0)	176.175	176.162	176.169	0.149
Julian's Total		79.0 (42.7)				

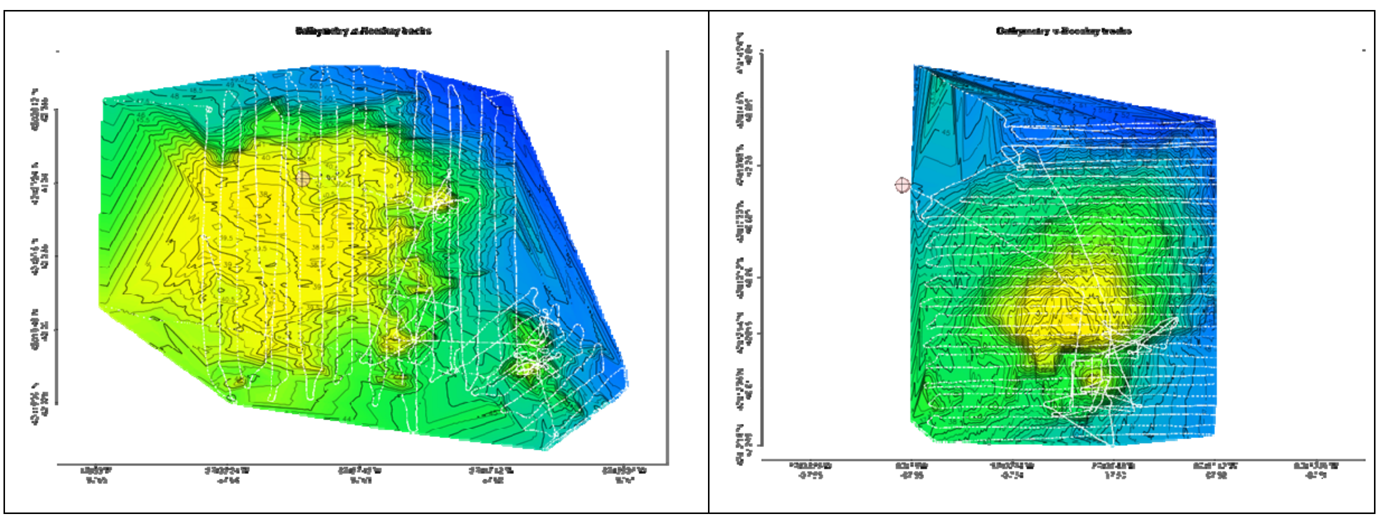


Figure 14. Real-time display of bathymetric data (uncorrected) over the Waukegan reef complex (left) and Julian's reef (right).

The corrected bathymetry data was imported into ArcScene, which allows 3D visualization of GIS data. 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 McDonnel 1998, Johhson et al. 2001). This interpolation is local (i.e. only surrounding points are included in analysis) and its predicted values are within the range of the data. Interpolation calculations were based on fitting a spherical or most appropriate model to the variogram. Bathymetric data from all study sites were displayed using 1-m depth contours and a vertical exaggeration value of 20 was used to aid visualization of the z dimension. Then, coverages of substrate deemed suitable for lake trout spawning were draped over the 3-D bathymetry surface and a TIN triangle (3D Analyst) was used to calculate slope (degrees) of potential habitat areas found at the study sites. Then, the Identify tool within ArcScene was used to locate areas where both substrate and slope (15-60°; Marsden et al. 1995a; Fitzsimons et al. 2003) suitable for lake trout spawning were found. Results of these analyses are presented below. Interactive, 3-D versions of Figures 15 and 16 were included with the report.

<u>Waukegan Reef Complex</u>

Water depths within the survey areas covering the Waukegan reef complex ranged from 37.6 to 54.5 m (Figure 15). In general, bathymetry throughout the survey areas was relatively gentle, and water depth was shallowest within the western portion of the survey area and deeper in the northeastern portion. The Waukegan reef complex lies in approximately 37-48 meters of water and areas containing substrate suitable for lake trout spawning were found throughout this depth range. Areas of suitable substrate within the Waukegan reef complex associated with 15-60º slope were composed of boulder-cobble piles and fractured bedrock debris and were primarily found clustered in the southeastern portion of the Waukegan reef survey area and the northern portion of the Waukegan South survey area (Figure 16). The slope of these patches of potential lake trout spawning habitat ranged from 15-53º and were found in 38-46 meters of water (Table 8).

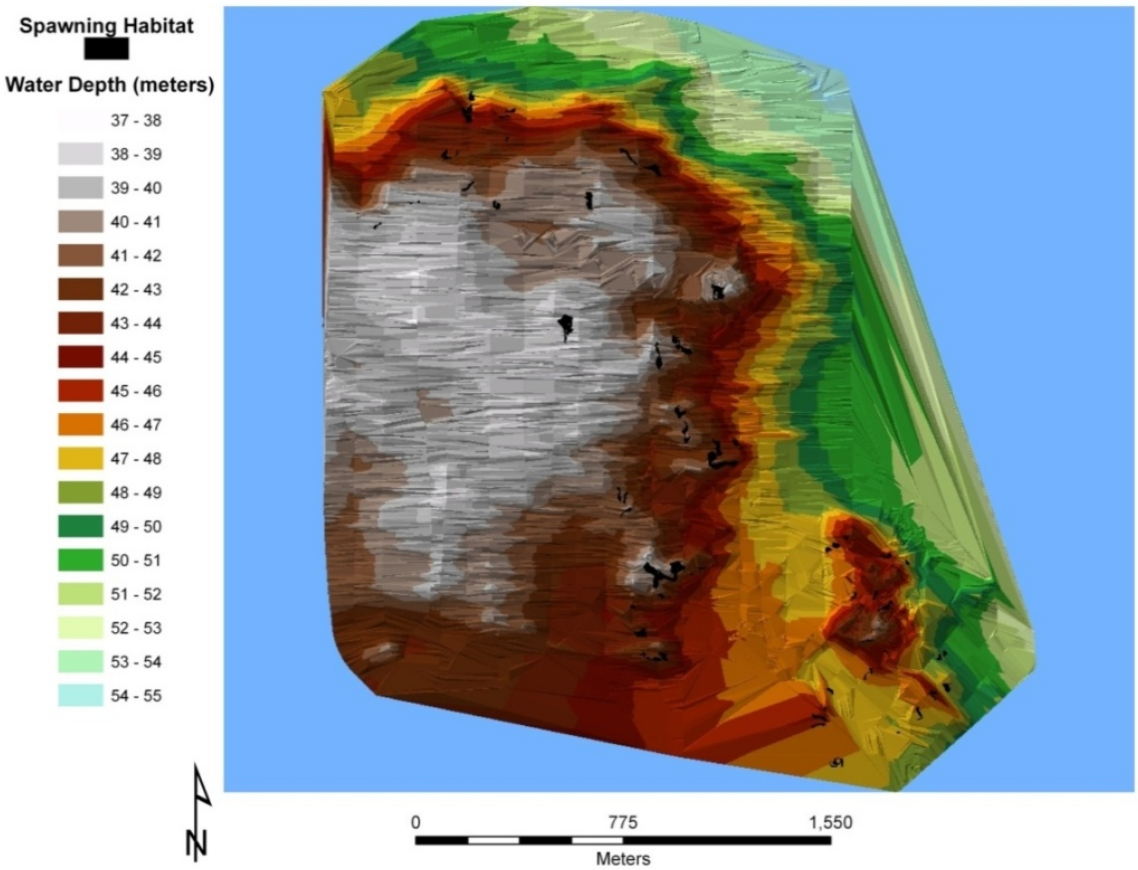


Figure 15. A 3-dimensional depiction of water depth (1 m contours) overlaid with potential lake trout spawning substrate (black areas) at the Waukegan reef complex.

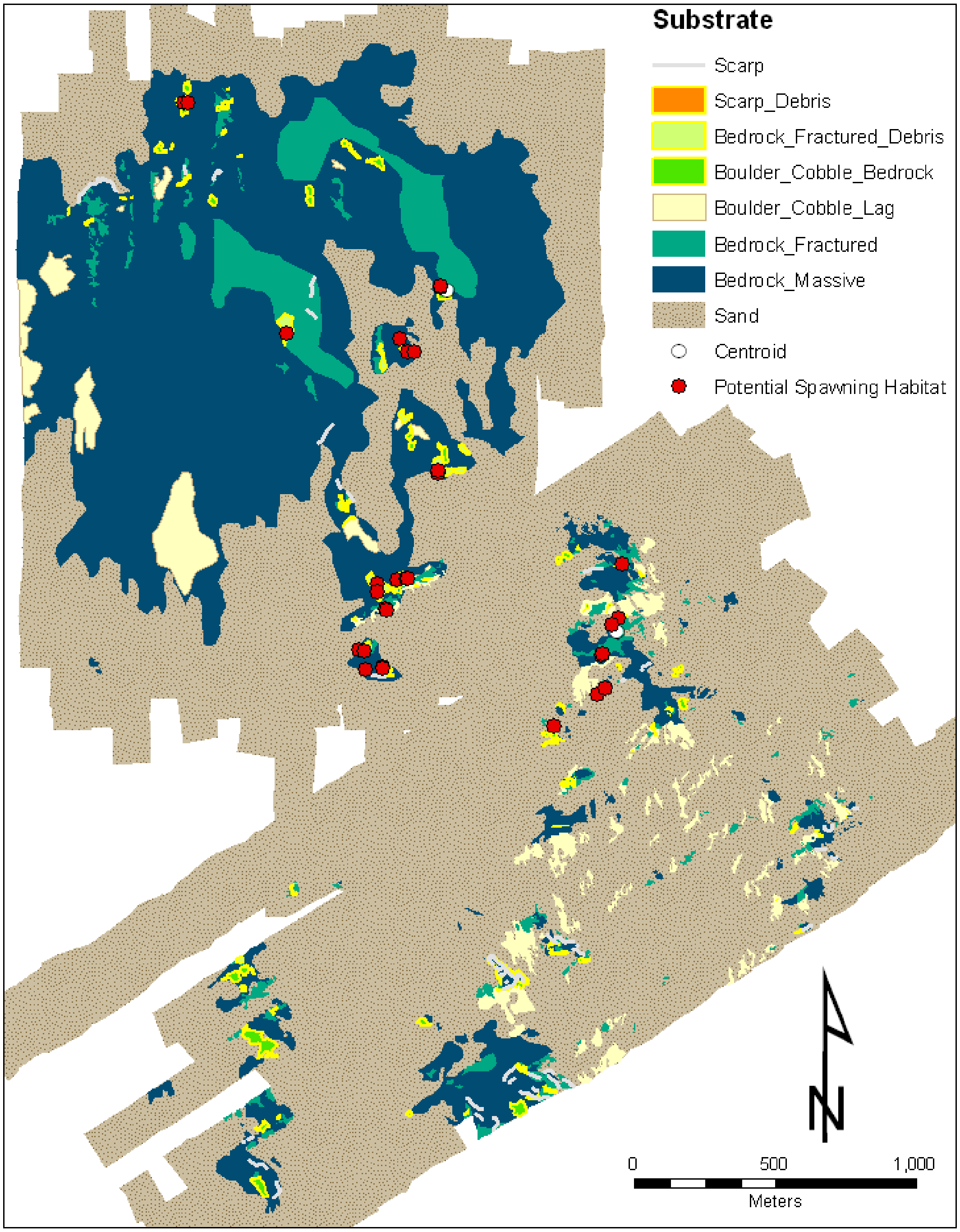


Figure 16. Map of the Waukegan reef complex illustrating locations with substrate and slope characteristics suitable for lake trout spawning (red circles).

Table 8. Summary of sites associated with substrate and slope suitable for lake trout spawning at the Waukegan reef complex. Coordinates are in UTM Zone 16N WGS 1984.

Substrate	Latitude	Longitude	Depth (m)	Slope (º)
Boulder-cobble	42.344511	-87.635394	46	33
Boulder-cobble	42.344506	-87.635553	46	15
Boulder-cobble	42.338678	-87.624394	40	15
Boulder-cobble	42.338650	-87.624394	40	15
Fractured bedrock debris	42.337119	-87.631039	38	15
Boulder-cobble	42.337003	-87.626150	42	15
Boulder-cobble	42.336597	-87.625547	42	32
Boulder-cobble	42.336567	-87.625806	42	20
Fractured bedrock debris	42.332789	-87.624483	41	40
Fractured bedrock debris	42.332703	-87.624461	42	20
Fractured bedrock debris	42.329853	-87.616447	45	24
Fractured bedrock debris	42.329339	-87.625717	42	38
Fractured bedrock debris	42.329322	-87.625728	42	30
Fractured bedrock debris	42.329311	-87.625783	42	18
Fractured bedrock debris	42.329272	-87.626211	41	17
Fractured bedrock debris	42.329161	-87.627039	40	24
Fractured bedrock debris	42.328906	-87.627039	41	48
Boulder-cobble	42.328369	-87.626672	43	15
Boulder-cobble	42.328303	-87.626656	43	24
Boulder-cobble	42.328092	-87.616611	43	15
Boulder-cobble	42.327911	-87.616911	43	25
Boulder-cobble	42.327036	-87.627797	44	24
Boulder-cobble	42.327011	-87.627606	43	24
Fractured bedrock debris	42.326953	-87.617303	43	38
Fractured bedrock debris	42.326931	-87.617383	43	25
Boulder-cobble	42.326489	-87.626800	43	17
Boulder-cobble	42.326472	-87.626797	43	53
Boulder-cobble	42.326386	-87.627528	43	26
Boulder-cobble	42.325886	-87.617186	46	26
Boulder-cobble	42.325681	-87.617503	47	17
Boulder-cobble	42.324625	-87.619353	46	15

Julian's Reef

Water depths within the Julian's reef survey area ranged from 25.0 to 56.6 m (Figure 17). Bathymetry changed relatively drastically throughout the survey area and the shallowest depths were recorded in the central portion of the survey area, which corresponds to the crest of Julian's reef. Julian's reef lies in approximately 25-45 meters and areas containing substrate suitable for lake trout spawning were found throughout this depth range. Areas of suitable substrate associated with 15-60º slope were composed of boulder-cobble piles and fractured bedrock debris and were primarily found along the eastern portion of Julian's reef (Figure 17). The slope of these patches of potential lake trout spawning habitat ranged from 15-29º and were found in 34-42 meters of water (Table 9).

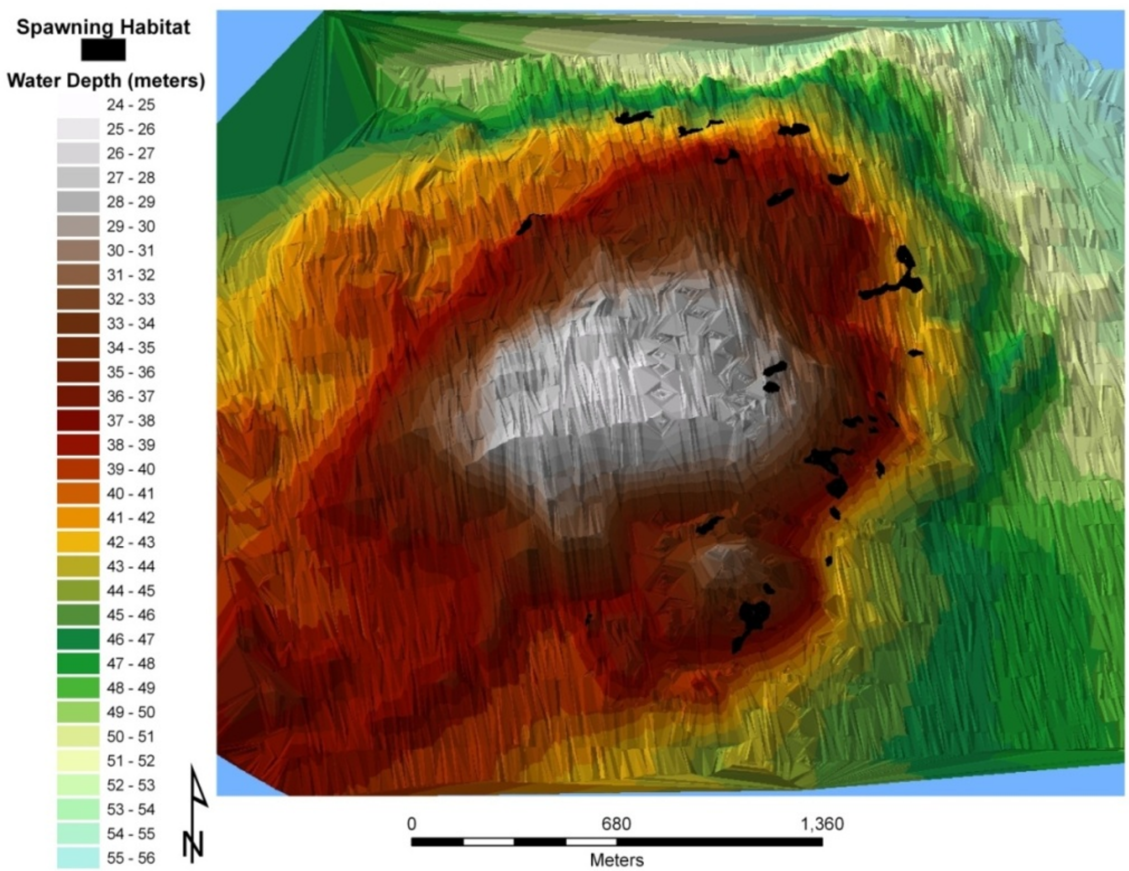


Figure 17. A 3-dimensional depiction of water depth (1 m contours) overlaid with potential lake trout spawning substrate (black areas) at Julian' reef.

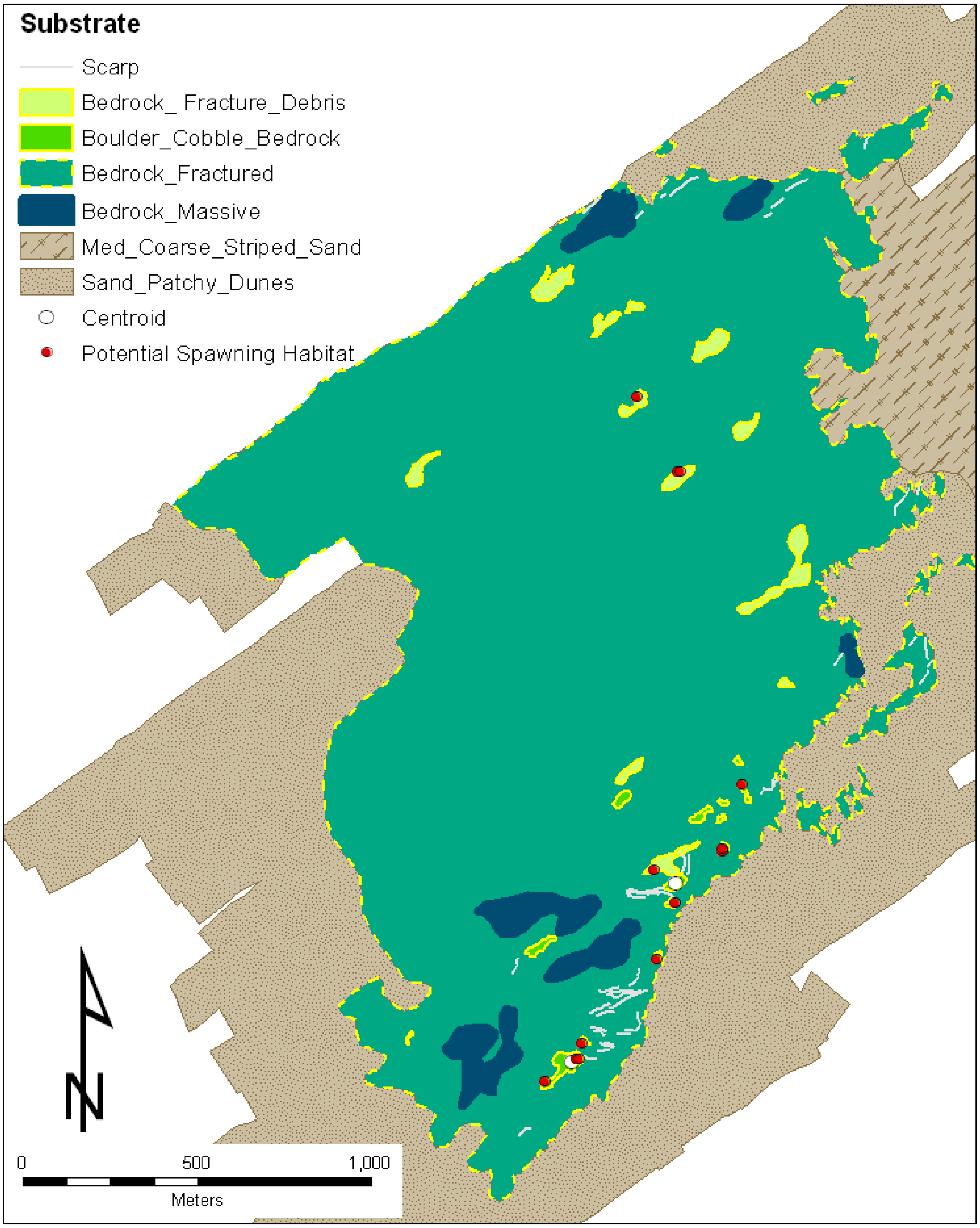


Figure 18. Map of Julian's reef illustrating locations with substrate and slope characteristics suitable for lake trout spawning (red circles).

Table 9. Summary of sites associated with substrate and slope suitable for lake trout spawning at Julian's reef. Coordinates are in UTM Zone 16N WGS 1984.

Substrate	Latitude	Longitude	Depth (m)	Slope (º
Fractured bedrock debris	42.226631	-87.529056	37	15
Fractured bedrock debris	42.224694	-87.527633	37	21
Fractured bedrock debris	42.224689	-87.527544	37	24
Boulder-cobble	42.216600	-87.525292	38	19
Boulder-cobble	42.214928	-87.525972	41	29
Boulder-cobble	42.214894	-87.525978	41	15
Boulder-cobble	42.214872	-87.525994	41	17
Fractured bedrock debris	42.214400	-87.528344	35	27
Boulder-cobble	42.213556	-87.527639	41	17
Boulder-cobble	42.212078	-87.528244	42	20
Boulder-cobble	42.209900	-87.530828	34	16
Boulder-cobble	42.209494	-87.531011	35	16
Boulder-cobble	42.209478	-87.530928	36	19
Boulder-cobble	42.208883	-87.532122	38	29

Task 5: Evaluation of egg deposition

During the summer of 2009, eighty deep-water egg traps were constructed following the design of Riley et al. (2010). The frame of each egg trap consisted of a 48 cm diameter hoop of 6 mm galvanized steel (Figure 19). The body of each trap was composed of a cylindrical piece of 3 mm mesh that was cinched closed 40 cm below of the frame using two 18 cm cable ties. Each trap was filled with 5 L of 5 cm plastic ‘bio barrels’ manufactured by Aquatic Eco Systems and then a 48-cm diameter piece of 2-cm polyethylene mesh was fastened to the top of the circular frame with cable ties. The ‘bio barrels’ were added to provide structure, aid entrainment of eggs, and hinder consumption of eggs by predators able to penetrate the polyethylene mesh lid. Each trap was weighted with two rings of 8-mm, 30 proof galvanized chain. The top chain was 150 cm long and was fastened to the steel frame with cable ties. Then, a 120 cm chain was attached with cable ties to the mesh body of the trap 15 cm below the steel frame. Ten egg traps were linked using nylon rope with 2.4 m spacing between each trap to create a gang; total sample length of a gang was 24 m. Four gangs were deployed at both the Waukegan reef complex and Julian’s reef; two of these gangs were deployed on substrate deemed suitable for lake trout spawning, while the other two gangs were deployed on substrate deemed not suitable. Suitability

Figure 19. Side (left panel) and top-view (right) of a deep-water egg trap used to evaluate lake trout egg deposition during the 2009 and 2010 spawning seasons.

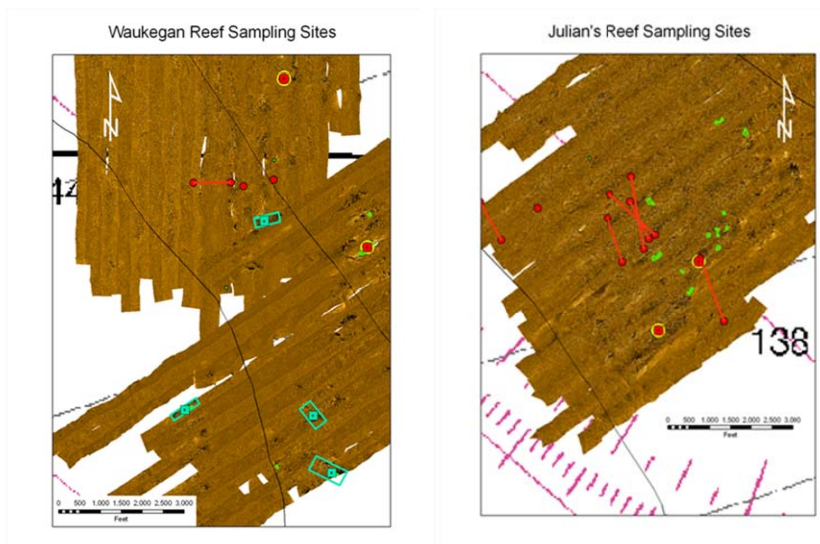


Figure 20. Egg trap and IDNR gill net sampling locations for the Waukegan reef complex (left) and Julian’s reef (right). Egg trap sites are depicted by a red square encompassed by yellow circle and IDNR gill net sites are represented by red circles and lines.

of the substrate and selection of egg traps sites was based on initial interpretation of sidescan sonar data combined with historical fish sampling data. The location of suitable sites and locations used for historical gill net sampling are provided for the Waukegan Reef Complex and Julian's Reef in Figure 20. During 2009, egg traps were deployed on October 20 and retrieved on November 4. During 2010, egg traps were deployed at the same locations on October 4 and retrieved on November 2 (Figure 21). Traps were disassembled back at the laboratory and examined for intact eggs and egg chorions. No intact eggs or egg chorions were collected in either year. However, invasive quagga mussels and round goby were collected during both years.

Figure 21. Deep-water egg traps on lake bottom shortly after deployment at Waukegan reef during the 2010 lake trout spawning season.

Task 6: Incorporate geo-referenced substrate and bathymetric data into Great Lakes GIS

All geospatial datasets are being sent to the Great Lakes GIS (GLGIS) and will be incorporated into the Lake Michigan GIS framework which is maintained by the Institute for Fisheries Research, University of Michigan, and Michigan Department of Natural Resources. http://ifrgis.snre.umich.edu/projects/GLGIS/support_docs/html/lake_GISs/LMGIS_index.htm.

Executive Summary

High resolution substrate and bathymetric maps were created for the Waukegan reef complex and Julian's reef using geo-referenced sidescan sonar, single beam sonar, and underwater video data. Although potential lake trout spawning habitat (desired substrate and slope) was found at all study sites, these areas were relatively small and scattered across each reef. The small size and patchy distribution of these areas made it very difficult to accurately sample and evaluate egg deposition on both reefs. Additionally, underwater video footage indicated that both reefs are extensively covered by dreissenid mussels and Cladophora spp. Thus, while suitable cobble-boulder piles and debris deposits were identified at the study sites using sidescan sonar, the extent to which these substrates may still provide suitable spawning habitat remains unknown. Spawning lake trout reportedly are attracted to clean substrate (Marsden et al. 1995) and in northeastern Lake Michigan lake trout egg deposition was shown to incrementally decrease as coverage of dreissenids increased from < 5% to >70% (Claramunt et al. 2011). Taken together, the small size of potential spawning habitat patches, along with extensive coverage of dreissenids at both reefs may at least partially explain why no lake trout egg deposition was documented during this study. Future research is needed to understand how these habitat alterations are impacting lake trout spawning behavior and egg survival as well the possible importance of nearshore areas for lake trout spawning.

Major findings

The objective of this study was to map the substrate and bathymetry of Waukegan and Julian's reefs and use this data to determine the location of potential lake trout spawning habitat. We also set out to measure egg deposition at these locations in an effort to inform future lake trout restoration work in Lake Michigan. Reconnaissance work at Waukegan reef revealed the presence of multiple undescribed bedrock areas south of the area originally associated with Waukegan reef. This region was added as an additional (third) study site and based on sidescan sonar data, portions of this site as well as Waukegan and Julian's reef contain areas that lake trout may use as spawning habitat. The predominant substrates deemed suitable for spawning within the three survey areas were boulder-cobble piles, fractured bedrock debris and scarp debris. These substrates were found in relatively small quantities scattered across each study site, which made it difficult to accurately sample potential spawning habitat for eggs and evaluate egg deposition on these reefs. Potential lake trout habitat 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 potential lake trout habitat totaled 65,444 m^2 within the Waukegan reef complex. This newly described area (Waukegan South) contributed significantly to identification of potential lake trout habitat in Illinois's offshore waters and was the only study site were scarp debris was found, which has been identified as good spawning habitat for lake trout in Lake Erie. On Julian's reef, potential lake trout habitat made up 2% (58,494 m^2) of the hard/coarse substrates, but fractured bedrock areas found on Julian's reef may also provide suitable lake trout spawning habitat. The sidescan sonar data does not have the resolution to identify potential habitat areas within fractured bedrock areas and it is anticipated that potential habitat within fractured bedrock areas would consist of relatively small and discrete patches located randomly across the reef. Overall, our results show 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 thought. Finally, all areas of potential spawning habitat found within the survey areas are located adjacent to deeper water areas that are assumed to serve as potential nursery habitat for lake trout in southern Lake Michigan.

Although suitable "substrate" near potential deep water nursery habitat was found at the study sites using sidescan, more detailed inspection with an underwater camera indicated these areas may no longer be suitable spawning "habitat" due to extensive coverage of dreissenids (*D. bugensis* found in egg traps) and Cladophora spp. Inspection of deep water egg traps also confirmed the presence of round goby at the study sites, but densities are unknown. A comparison of the images Edsall et al. (1996) captured of cobble-boulder piles on Julian's reef during the 1990s and those captured during this study help to illustrate the major alteration invasive species have brought about over the last decade. Currently, interstitial spaces, which are essential for lake trout eggs to develop properly, may be clogged with fine silt and pseudofeces from dreissenids. Round goby may also negatively impact the success of lake trout reproduction on the study sites as they are a known predator of lake trout eggs. 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 invasives remains unknown. The presence of lithophillic species can reduce energy associated with waves and currents over coarse substrates causing an increase in siltation, especially in interstitial spaces which are necessary for protection of lake trout eggs. Siltation may be augmented by dreissenid pseudofeces. Siltation reduces the volume of interstitial space available and may suffocate eggs that are deposited there. However, the extent of negative impact these alterations may have on lake trout eggs has not been empirically tested and thus remains largely unconfirmed.

Taken together, the small size of the potential spawning habitat patches and major habitat alteration by invasive species may explain the lack of egg deposition over suitable substrate at Illinois's deep water reefs. These and other deep water areas which were once thought of as historical spawning grounds may no longer provide habitat suitable for successful spawning and reproduction of lake trout. Similar work in Lake Erie suggested a shift in spawning at deep water sites to high-energy nearshore areas, which are associated with a lower density of lithophillic species and reduced siltation of interstitial spaces (Biberhofer et al. 2010). Similarly, 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 dreissenids, may have a greater potential to contribute to spawning success than deeper water habitat. In southwestern Lake Michigan, exposed bedrock areas and manmade structures within Illinois's nearshore waters may now provide some of the best available spawning habitat for lake trout. However, the densities of round goby in nearshore areas of southwestern Lake Michigan have increased dramatically over the last several years (Sara Creque INHS, personal communication, 2011) and their impact as egg predators might be significant in these areas.

Management implications

Our results suggest that the Waukegan reef complex provides as much potential lake trout spawning habitat as Julian's reef. Additionally, catch rates of lake trout at Waukegan reef are typically higher compared to Julian's reef (Steve Robillard IDNR, personal communication, 2012). Thus, the Waukegan reef complex should be considered a significant portion of Illinois's offshore lake trout spawning grounds and as such should be considered as a possible additional location for stocking lake trout within Illinois waters. Final data from sidescan sonar and bathymetric surveys were provided to the IDNR for consideration of potential sites for their annual lake trout spawning assessment surveys.

Future research

This project has provided valuable insights on the current status, quality and quantity of potential lake trout spawning substrate on Illinois's offshore reefs. It also provided the first detailed substrate and bathymetry map of Waukegan reef; the last mapping of this reef was the hydrographic map compiled from 1946 USACE soundings. However, due to the extensive coverage of invasive species on these reefs it is now crucial to understand how these habitat alterations are affecting lake trout spawning behavior, egg deposition and most importantly egg survival rate.

Virtually no work has been done on lake trout nursery habitat and this lack of data severely limits our ability to assess the importance of connectivity to spawning habitat. Thus, a suite of studies to identify and evaluate lake trout nursery habitat and connectivity to spawning habitat would be consistent with goals of the Great Lakes Fish and Wildlife Restoration Act of 2006 to restore fish resources within the Great Lakes Basin and would involve rehabilitation of lake trout in support of *A Fisheries Management Implementation Strategy for the Rehabilitation of Lake Trout in Lake Michigan* and the Lake Michigan Fish Community Objectives.

Presentations

Redman, R., S. J. Czesny, and S. D. Mackey. 2010. An evaluation of lake trout (*Salvelius namaycush*) spawning habitat: are southern Lake Michigan's offshore reefs suitable? International Association of Great Lakes Research, Toronto, ON (poster presentation).

An electronic version of this poster presentation was included with the hard copy of the report (CD1).

Relevant images: Electronic versions of all imagery and photographs that appear within the report were included with the hard copy of the report (CD 1).

Geographic region: All data collection was conducted in and around two bedrock reefs that lie within Illinois waters of Lake Michigan: 1) Waukegan reef and 2) Julian's reef. Below are coordinates for boundaries of each reef; coordinates are in UTM Zone 16N WGS 1984 (decimal degrees).

Reef	Northwest	Northeast	Southeast	Southwest
Waukegan Complex	42.350222 -87.651383	42.350027 -87.599222	42.304198 -87.599912	42.304795 -87.652035
Julian's	42.234405 -87.547522	42.234405 -87.515363	42.205618 -87.515363	42.205617 -87.547522

Reports

Redman, R., S. D. Mackey, and S. J. Czesny. 2009. Evaluation of lake trout spawning reef suitability in Illinois waters of Lake Michigan. First Annual Progress Report to the U.S. Fish and Wildlife Service.

Redman, R. S. D. Mackey, and S. J. Czesny. 2010. Evaluation of lake trout spawning reef suitability in Illinois waters of Lake Michigan. Second Annual Progress Report to the U.S. Fish and Wildlife Service.

Redman, R. and S. J. Czesny. 2010. Exploring offshore reefs in Illinois waters of Lake Michigan: Are they suitable for lake trout spawning? Illinois Natural History Survey Reports. No. 403.

An electronic version of these completed reports and article was included with the hard copy of the report (CD1).

References

Biberhofer, H., and 5 coauthors. 2010. Identifying potential lake trout spawning habitat in Lake Erie. Great Lakes Fish and Wildlife Restoration Act Final Report. 24p.

Bronte, C. R., and 11 co-authors. 2003. Possible impediments to lake trout restoration in Lake Michigan. Lake Trout Task Group Report for the Lake Michigan Committee. Great Lakes Fishery Commission.

Burrough, P.A. and R.A. McDonnell. 1998. Principles of Geographical Information Systems. Oxford University Press.

Claramunt, R. M., J. L. Jonas, J. D. Fitzsimons, J. E. Marsden. 2005. Influences of spawning habitat characteristics and interstitial predators on lake trout egg deposition and mortality. Transactions of the American Fisheries Society 134(4):1048-1057.

Coble, D. W., R. E. Brueswitz, T. W. Fratt, and J. W. Scheirer. 1990. Lake trout, sea lamprey, and overfishing in the upper Great Lakes: a review and reanalysis. Transactions of the American Fisheries Society 119:985-995.

Collinson, C., R. D. Norby, and A. K. Hansel. 1979. Continued evaluation of Silurian reefs in Lake Michigan as potential breeding sites for lake trout. Illinois State Geologic Survey report.

Dawson, K. A., R. L. Eshenroder, M. E. Holey, and C. Ward. 1997. Quantification of historic lake trout (Salvelinus namaycush) spawning aggregations in Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences 54:2290-2302.

Edsall, T. A., G. W. Kennedy, and W. H. Horns. 1996. Potential spawning habitat for lake trout on Julian's Reef, Lake Michigan. Journal of Great Lakes Research 22(1):83-88.

Eshenroder, R. L., M. E. Holey, T. K. Gorenflo, and R. D. Clark, Jr. 1995. Fish-community objectives for Lake Michigan. Great Lakes Fish. Comm. Spec. Pub. 95-3. 56p.

Eshenroder, R. L., and M. K. Burnham-Curtis. 1999. Species succession and sustainability of the Great Lakes fish community. Pages 145-184 in W. W. Taylor and C. P. Ferreri, editors. Great Lakes fisheries policy and management, a binational perspective. Michigan State University Press, East Lansing.

Fitzsimons, J. D., J. E. Marsden, B. J. Ellrott, J. Jonas, and R. M. Claramunt. 2003. Effects of egg and fry predators on lake trout recruitment in Lake Michigan. Great Lakes Fishery Commission Final Report, Ann Arbor, 239 p.

Frye, C. 2008. Minimum Bounding Rectangle (MBR) Analysis tools, http://arcscripts.esri.com/details.asp?dbid=15502.

Hansen, M. J. 1999. Lake trout in the Great Lakes: basinwide stock collapse and binational restoration. Pages 417-454 in W. W. Taylor and C. P. Ferreri, editors. Great Lakes fisheries policy and management, a binational perspective. Michigan State University Press, East Lansing.

Holey, M. E., and 8 coauthors. 1995. Progress toward lake trout restoration in Lake Michigan. Journal of Great Lakes Research 21(Supplement 1):128-151.

Johnston, K., J.M. Ver Hoef, K. Krivoruchko, and N. Lucas. 2001. ArcGIS 9 Using ArcGIS Geostatistical Analyst.ESRI Press.

Marsden, J. E. 1994. Spawning by stocked lake trout on shallow, near-shore reefs in southwestern Lake Michigan. Journal of Great Lakes Research 20:377-384.

Marsden, J. E., and M. A. Chotkowski. 2001. Lake trout spawning on artificial reefs and the effect of zebra mussels: fatal attraction. Journal of Great Lakes Research 27:33-43.

Meadows, G.A., S. D. Mackey, R. R. Goforth, D. M. Mickelson, T. B. Edil, J. Fuller, D. E. Guy, Jr., L. A. Meadows, E. Brown, S. M. Carman, and D. L. Liebenthal. 2005. Cumulative Impacts of Nearshore Engineering. Journal of Great Lakes Research 31 (Supplement 1):90-112.

Riley, J. W., N. F. Thompson, J. E. Marsden, and J. Janssen. 2010. Development of two new sampling techniques for assessing lake trout reproduction in deep water. North American Journal of Fisheries Management 30(6):1571-1581.

Wells, L., and A. L. McLain. 1972. Lake Michigan: effects of exploitation, introductions, and eutrophication on the salmonid community. Journal of the Fisheries Research Board of Canada 29:889-898.