Lake Trout Spawning on Artificial Reefs and the Effect of Zebra Mussels: Fatal Attraction?

J. Ellen Marsden1,*, and Michael A. Chotkowski2

Lake Michigan Biological Station
Illinois Natural History Survey
400 17th St.
Zion, Illinois 60099

ABSTRACT. Lake trout stocked in the Great Lakes appear to spawn primarily on shallow reefs (< 16 m deep), particularly on breakwaters or water intake lines. Shallow water substrates are being rapidly colonized by zebra mussels, potentially resulting in degraded substrate and interstitial water quality. The attraction of spawning lake trout to new substrate and the effect of zebra mussels on spawning success was examined. Lake trout eggs and fry were collected on clean cobble and cobble fouled with zebra mussels at the Port of Indiana in southern Lake Michigan, and on each of three recently constructed submerged reefs. Egg deposition was similar among all sites except on new, unfouled cobble, where deposition was 11 to 29 times higher, depending on the collection device used. The ratio of empty egg chorions to intact eggs was similar among all sites except the fouled substrate, where the ratio was 129× higher (P < 0.001). Fry catches were similar on fouled and unfouled substrate, but 6.5 × higher on one of the new reefs (P < 0.01). In laboratory incubators, egg hatching rates were similar in cobble with and without zebra mussels. Lake trout were attracted to spawn on newly constructed artificial reefs, but the presence of zebra mussels appeared to reduce egg deposition and increase damage to eggs. Artificial reefs may successfully increase the amount of spawning substrate available for lake trout, but if they are constructed in shallow water they may not be productive areas for egg incubation and fry hatch due to the presence of zebra mussels, shallow-water egg and fry predators, and storm surge.

INDEX WORDS: Lake trout, zebra mussels, artificial reefs, spawning.

INTRODUCTION

Lake trout (Salvelinus namaycush) are native to the Great Lakes, but were extirpated from all of the lakes except Superior and parts of Lake Huron by the late 1960s due to overfishing and predation by introduced lamprey (Petromyzon marinus). The importance of this species to the ecology and fisheries of the Great Lakes has motivated extensive annual stocking of lake trout by state, provincial, and federal management agencies since 1965. Efforts to restore self-sustaining populations of lake trout to the lower four Great Lakes have failed to produce measurable recruitment of wild fish. Lake trout eggs and fry have been found at numerous locations around the lakes, but primarily at shallow sites, i.e., less than 16 m deep (Holey et al. 1995, Schreiner et al. 1995). Eggs spawned on shallow sites may be vulnerable to a number of factors including wave action, sedimentation related to human activities (construction, dredging, land use), and a variety of predators which are absent or rare on deep reefs in spring (Jones et al. 1995). Potential predators of eggs and fry include exotic species, such as alewife (Alosa pseudoharengus), carp (Cyprinus carpio), and round gobies (Neogobius melanostomus) (Krueger et al. 1995, Marsden 1997, Chotkowski and Marsden 1999).

A large proportion of the shallow sites on which lake trout eggs and fry have been collected are man-made structures such as breakwaters and water intake lines (Schreiner et al. 1995, Marsden et al. 1995). The possibility that spawning on these “artificial reefs” may enhance restoration by increasing reproductive output has received considerable re-
The recent addition of zebra and quagga mussels (*Dreissena polymorpha* and *D. bugensis*) to the fauna of the Great Lakes poses a potential new threat to lake trout egg incubation on shallow reefs. By extension, they also threaten egg incubation on man-made structures including artificial reefs, as the majority of these structures are constructed in shallow water in the Great Lakes (<15 m). Zebra mussels are now present on most of the shallow reefs in the lower Great Lakes, in densities varying from a few individuals per square meter to mats over 5 cm thick (Call 1996, pers. obs). At higher densities, zebra mussels encrust cobble substrates so thickly that they occlude interstitial spaces. If lake trout eggs cannot settle into interstices, they are vulnerable both to predation and to damage and dislodgment by wave action. Any eggs that do settle into substrate fouled by zebra mussels may be suffocated by the deposition of feces and pseudofeces, or by local deoxygenation caused by reduced circulation and organic breakdown of these materials. If, as has been suggested elsewhere (Marsden and Krueger 1991), adult lake trout evaluate the cleanliness of the substrate prior to spawning, they may avoid spawning on substrates heavily fouled by zebra mussels. To date, no studies have examined the effect of zebra mussels on lake trout spawning or egg incubation.

Evaluation of the effect of zebra mussels on lake trout spawning and egg incubation in the field is problematic, because fouled and unfouled reefs do not both occur in the same time and place. Once zebra mussels become established in a body of water, they rapidly colonize any available hard substrate. Thus, a comparison would either require study of reefs in two different lakes, or study of one reef over a period of time prior to and following colonization. Both approaches would incur problems with interpretation of the data. In 1995, a renovation of the Port of Indiana breakwater at the southern end of Lake Michigan by the Army Corps of Engineers offered a unique opportunity to study adjacent, virtually identical substrates, fouled and unfouled by zebra mussels. Lake trout were already known to aggregate near and spawn on cobble substrate at the base of the west breakwater (Marsden 1994). Egg deposition at this site in 1992 was ten times higher than at six natural sites along the southern shoreline of Lake Michigan, and fry were collected at the site in 1993. By summer, 1993, zebra mussels densely covered most of the cobble. In 1995, the Army Corps of Engineers began a rehabilitation of the breakwater to reduce the transmission of wave energy into the harbor. In the first phase, which was begun and completed in 1995, new cobble-rubble was added to approximately one third of the western breakwater to shore it up (Fig. 1). In the second phase, which began in 1995 and was scheduled to terminate in 1998, seven submerged barrier reefs were constructed 24 m from the outside of the north breakwater (Fig. 1). The bedding stone at the base of these reefs encompasses the size range (15 to 50 cm diameter) of bedding stone which forms the base of the existing west-facing breakwater where lake trout eggs and fry were previously collected. The size of the bedding stone is ideal to create interstitial spaces which will protect lake trout eggs over the winter (Marsden and Krueger 1991). Thus, the opportunity to compare egg deposition and fry emergence on existing fouled substrate and new, unfouled substrate was presented.

This study had two objectives: to determine how soon and to what extent lake trout will spawn on a newly constructed artificial reef, and to evaluate the effect of zebra mussels on lake trout spawning and egg incubation. The following specific questions were addressed: (1) Given that lake trout spawn nearby on the west-facing breakwater, how soon
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after construction would they “find” the barrier reefs and begin to spawn on the newly-deposited substrate? (2) Would egg deposition be higher on the new, unfouled substrate compared with zebra mussel-fouled substrate? (3) Would fry hatch be greater on the new substrate compared with the existing fouled substrate?

METHODS

Study Site

The Port of Indiana breakwater consists of a 1-km-long north-south breakwater, contiguous at its north end with a 1.2 km breakwater running approximately east-north-east (Fig. 1). The southernmost third of the north-south breakwater is constructed of stone-filled sheet pilings with no apron stone (see below), and was not part of the study area. In cross section, the west-facing breakwater is constructed as a loose, emergent pile of 9 to 14 metric ton rectangular blocks of limestone (armor stone), laid on a graded series of smaller blocks. At the base of the outside of the breakwater (hereafter referred to as the west breakwater), an apron of 2 to 41 kg sub-angular bedding stone extends irregularly 3 to 13 m from the anchor stone, and varies from one cobble deep to over 3 m deep. The bedding stone is 15 to 50 cm in diameter, and resembles rubble-cobble substrates found on natural spawning reefs in the Great Lakes (Marsden and Krueger 1991, Edsall et al. 1992, Fitzsimons 1995). The base of this section of breakwater is 13 m deep at the north end, gradually rising to 6 m where the bedding stone ends at the south. The north-facing breakwater consists of armor stone laid directly on sand-silt substrate. In places small piles of cobbles in the interstices of the armor stone suggest that some bedding stone may have been laid during the original construction, completed in 1968. In the interior of the harbor, the substrate adjacent to both breakwaters is silt and mud, with no evidence of cobbles.

Eggs and fry along the northern third of the west breakwater (Fig. 1) were collected beginning in 1993 to measure spawning intensity on the undisturbed site prior to new construction by the Army Corps of Engineers. In 1995, new cobble and armor stone was added to the center section of the west breakwater, and construction began on the first of seven barrier reefs along the outside of the north-facing breakwater. The barrier reefs are located in 13 to 14 m water depth and rise to approximately 7 m below the lake surface (Fig. 2). Each barrier reef consists of a 3-m-deep layer of 0.5 to 40 kg rubble with a cap of 8 to 10 metric ton armor stone blocks. The rubble apron extends beyond the armor stone cap in a belt 10 to 15 m wide. Each barrier reef was designed to be 115 m long by 30 m wide, with the long axis parallel to the existing breakwater and 30 m between each reef (Fig 1). In fact, during the sonar survey of the site, the first, easternmost reef appeared to be somewhat longer than the subsequently built reefs. The first reef and part of the

FIG. 1. Diagram of the Port of Indiana breakwater on the south shore of Lake Michigan, showing location of submerged barrier reefs. Unfilled barrier reef outlines indicate sites of future barrier reefs. Shaded area on the west breakwater indicates location of new substrate placed in 1995. Years indicate dates of construction or substrate placement.

FIG. 2. Cross-sectional view of submerged reefs in relation to main breakwater at the Port of Indiana, Lake Michigan.
second were completed by 1 Oct. 95; in 1996 the second reef and a third were completed. These reefs, are designated in order of construction from east to west, as NR1, NR2, and NR3.

Zebra Mussel Densities

During the first visual survey of the west breakwater on 1 December, 1992, the substrate was observed by divers to be covered with a monolayer of zebra mussels. Zebra mussel abundance and density steadily increased, and by 1994 averaged 41,147/m² ± 13,340 (maximum 68,847/m²) on the armor stone blocks (Call 1996).

In November 1996 five cobbles were collected from each of the fouled and unfouled portions of the west breakwater, NR1, and NR2 by diving. Densities of zebra mussels were estimated in each area by counting mussels in 5 replicate 20 cm² quadrats from each substrate sample. Lengths of 168 to 606 zebra mussels from each area were measured.

Egg Collections

Eggs were collected in 1993 to 1995 using egg nets (Horns et al. 1989) and egg traps (Marsden et al. 1991); due to damage to the egg traps in severe weather, only egg nets were used in 1996. Egg bags (Perkins and Krueger 1994) were used in 1994 and 1996, when weather permitted their installation and retrieval. Egg nets and traps lie on top of the substrate, where they passively collect and retain eggs; both devices are 20 cm in diameter, and are set from the surface on buoyed lines. These devices do not permit access by predators. Probability of egg capture and retention in each device is unknown, therefore data were compared among egg traps and nets as relative catch-per-unit-effort (CPUE). Egg bags, 32 cm in diameter, are individually buried into substrate by a diver, and eggs within the enclosed substrate may be eaten by predators or dislodged and removed by currents. Thus, the numbers of eggs the bags collect are presumably more representative of natural egg densities in the substrate. In 1993, one gang of 25 egg nets and 25 egg traps attached alternately at 1.6 m intervals on a 80 m line was set along the west breakwater; in 1994 and 1995, two gangs were set. Eight egg bags were also buried on the west breakwater in 1994. In 1996 gangs comprised of only 25 egg nets each were used; one gang was deployed on the west breakwater fouled substrate, one on the west breakwater clean substrate, and one each on NR1, NR2, and NR3. Five egg bags each were deployed on fouled and clean substrate on the west breakwater and on NR1 and NR3. The bags on the west breakwater were set in small clusters, with approximately 0.5 between bags and 4 m between the cluster on fouled substrate and the cluster on unfouled substrate. All egg collecting gear was deployed between late September and late December, though dates of deployment varied from year to year.

Variation in egg CPUE among the years 1993 through 1997 was evaluated for the net/trap gear by one-way anova followed by Tukey multiple comparisons tests. Log-transformation of the data did not alter the ANOVA results. Comparison of egg deposition between west breakwater fouled (WWF) and unfouled (WWU) substrates, and the new reefs NR1, NR2, and NR3 was only possible in 1996; differences among site means were evaluated by separate one-way ANOVAs for nets/traps and bags, followed where appropriate by Tukey multiple comparisons tests.

A large number of chorions, representing damaged eggs that had lost their yolk, was found in the collecting gear. Dead (opaque) eggs were also collected, but could have been damaged in transit in the collecting gear. To investigate whether frequencies of egg damage differed among sites, the ratio of catch per effort of egg chorions to intact eggs was compared among sites for both gears in the 1996 data, with the ratio separately computed for each observation; equality of means was tested separately for net/trap and bag gear types, followed where appropriate by Tukey multiple comparisons tests.

Fry Collections

Lake trout fry were collected in spring, 1993 and 1995 through 1997, using two types of emergent fry trap. “Old” traps had a 51-cm-square base of angle-iron, with metal mesh sides tapering to a collection bottle at the top (Marsden et al. 1988). These traps were deployed with individual buoy lines, and were checked by lifting them to the surface every 5 to 14 days. The “new” traps had a similar basic design to the old traps, except that the base was a 60 cm diameter circle of 5 cm OD corrugated sand-filled plastic hose, and the non-rigid sides were constructed of Delta™ nylon mesh fabric. These traps were checked by a diver every 5 to 18 days. The collection area under the old traps was 0.26 m², and under the new traps was 0.28 m². In 1993 and 1995,
25 and 36 old traps were deployed in late April on the fouled west breakwater only, and lifted on 4 May 1993 and 2 June 1995. In 1996, from 4 to 29 old traps were deployed on the fouled west breakwater, NR1, and NR2 from mid April to early May, and retrieved on 6 June. In 1997, 7 or 8 traps were deployed on the fouled and unfouled portions of the west breakwater and NR1 on 12 May 1997, and retrieved on 11 June 1997.

Variation in site fry CPUE means was evaluated for 1996 data by one-way ANOVA followed by a Tukey multiple comparisons test. There was an unexpected interaction between device-type and site in the 1997 data; consequently, the 1997 data were analyzed by separate one-way ANOVAs on the old and new device data.

**Laboratory Egg Incubation**

In 1996, two 1 m³ cribs were constructed in an 4,164 L raceway fed with raw Lake Michigan water. Flow rate through the raceways was approximately 20 L/min. Each crib was filled to 1 m depth with cobbles similar in size and geologic material to those at the Port of Indiana breakwater. Zebra mussels (12.4 kg) were collected from the Port of Indiana breakwater, added to the downstream crib, and allowed to attach to the substrate. This quantity of zebra mussels produced a density in the cribs that was equivalent to the density observed at the breakwater. Eggs and milt were collected from wild-caught lake trout during annual gillnetting assessments by the Illinois Department of Natural Resources to provide fertilized eggs for laboratory experiments. Fifty eggs were placed into each of 18 incubators (Manny et al. 1989, modified by Sly and Evans 1996). Six incubators were placed vertically, long side uppermost, into the cobbles in each of the cribs on 27 October 1996. An additional six incubators were suspended in the same orientation in the raceway, upstream of the cribs. The incubators were removed on 19 March 1997, and checked for live fry. Numbers of hatched fry were compared among the treatments using a one-way ANOVA.

## RESULTS

### Zebra Mussel Densities

In 1996, when egg collections and subsequent fry collections were focused on comparing fouled and unfouled substrates, zebra mussels were present on all available cobbles at the Port of Indiana. Numerically, zebra mussels were least dense on the fouled west breakwater substrate (18,034 ± 9,146/m²) and NR 2 (17,117 ± 9,494/m²), and most dense on NR1 (61,742 ± 18,052/m²) and the unfouled west breakwater (30,769 ± 19,758/m²; Table 1). However, absolute densities are misleading, because the majority of the zebra mussels on the new cobbles (west breakwater, NR1, and NR2) were young-of-the-year juveniles, and comprised very little biomass. The abundance of large zebra mussels is a better indicator of biomass; 14,875 ± 8,819/m² mussels > 9 mm long were present on the fouled substrate, compared to 204 ± 279 to 1,426 ± 1,815/m² on the unfouled substrates (Table 1).

![Table 1](image)

**Table 1.** Size distribution and density of zebra mussels on cobble substrate at the Port of Indiana, measured in November 1996. Numbers represent mean number of zebra mussels counted in five replicate 20 cm² samples. WWF = west breakwater fouled (old) substrate, WWU = west breakwater unfouled (newly deposited) substrate, NR1 and NR2 = newly constructed barrier reefs.
Divers noted that the thickness of the zebra mussel layer on fouled substrate was approximately 2 cm on horizontal surfaces and 5.5 cm on vertical surfaces (Call 1996), and interstitial spaces were completely occluded. In contrast, the tiny zebra mussels on the unfouled substrates formed only a thin veneer on the cobbles. The appropriate measure to quantify the difference in impact of small and large zebra mussels on substrate would be colony volume per unit area.

**Egg Collections**

In the 4 years of egg collections (1993 through 1996), 30 to 6,500 eggs were collected annually (CPUE 0 to 26.1 eggs/device/day for individual devices), in addition to large numbers of empty chorions (Table 2). Egg CPUE for bags was uniformly higher than for nets/traps. Egg CPUE for the net/trap gear alone on the fouled west breakwater was significantly higher in 1995 than in other years (F<sub>0.05(2), 3, 306</sub> =12.1, P < 0.001; Table 2). In 1996, egg CPUE for the whole season using egg nets was identical among fouled west breakwater substrate, NR1, NR2, and NR3 (pooled mean 0.16 ± 0.42 eggs/device/day), but was 11× higher on unfouled west breakwater substrate (mean 1.81 ± 2.68 eggs/device/day; F<sub>0.05(2), 4, 126</sub> = 9.59, P < 0.001, Tukey test). Egg CPUE using bags followed the same pattern; WWF, NR1, and NR3 were identical (pooled mean 0.54 ± 0.80 eggs/device/day) and WWU was approximately 29× higher (mean 15.7 ± 7.5 eggs/device/day; F<sub>0.05(2), 3, 16</sub> = 19.74, P < 0.001, Tukey test). Although there were age differences of up to 1.5 years among the new reefs, with the newest reef (NR3) completed only a few months before the 1996 lake trout spawning season, there did not appear to be a relationship between the age of a reef and the egg deposition rate upon it, using either net/trap or bag gears.

The ratio of numbers of empty egg chorions to numbers of intact eggs in egg bags did not differ among WWF, WWU, NR1, and NR3 in 1996 (0.39 ± 0.45 chorions/egg; F<sub>0.05(2), 3, 16</sub> = 1.91, P < 0.18). In the net/trap gear, the ratio was indistinguishable among WWU, NR1, NR2, and NR3 (0.004 ± 0.002 chorions/egg), but was over 100× higher on WWF (0.52 ± 0.17 chorions/egg; F<sub>0.05(2), 4, 51</sub> = 11.12, P < 0.001, Tukey test). High proportions of chorions were also noted on WWF in 1993, 1994, and 1995. Proportion of live eggs in all gear was high (94 to 100%) at all sites in all years except on WWF in 1994 (67% in nets/traps, 68% in bags), and on WWF in 1996 (79% in bags).

**Fry Collections**

Zero to 215 fry were collected annually (Table 3). Individual device CPUEs on the fouled west breakwater, the only site that was sampled every year, varied from zero to 3.67 fry/device/day. In the spring of 1996, before clean cobble was added to **Table 2. Numbers of lake trout eggs and chorions collected at the Port of Indiana breakwater in southwestern Lake Michigan. CPUE is reported as catch per device per day. WWF = west breakwater fouled substrate, WWU = west breakwater unfouled substrate, NR1, NR2, and NR3 are the three barrier reefs constructed outside the north arm of the breakwater (Fig. 1). Chorion ratio = # chorions/# eggs.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Date set</th>
<th>Date lifted</th>
<th>Collection gear</th>
<th># Devices set/ retrieved</th>
<th>Total eggs</th>
<th>% Live eggs</th>
<th>Total chorions</th>
<th>CPUE (eggs only)</th>
<th>Chorion ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>WWF</td>
<td>12 Nov.</td>
<td>23 Nov.</td>
<td>nets+traps</td>
<td>50/50</td>
<td>30</td>
<td>100</td>
<td>275</td>
<td>0.05</td>
<td>9.2</td>
</tr>
<tr>
<td>1994</td>
<td>WWF</td>
<td>07 Oct.</td>
<td>01 Dec.</td>
<td>nets+traps</td>
<td>100/100</td>
<td>127</td>
<td>67</td>
<td>28</td>
<td>0.03</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 Oct.</td>
<td>20 Dec.</td>
<td>bags</td>
<td>8/8</td>
<td>742</td>
<td>68</td>
<td>98</td>
<td>1.3</td>
<td>0.13</td>
</tr>
<tr>
<td>1995</td>
<td>WWF</td>
<td>17 Oct.</td>
<td>29 Nov.</td>
<td>nets+traps</td>
<td>100/61</td>
<td>1,770</td>
<td>96</td>
<td>262</td>
<td>0.7</td>
<td>0.15</td>
</tr>
<tr>
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<td>WWF</td>
<td>16 Oct.</td>
<td>19 Nov.</td>
<td>nets</td>
<td>25/25</td>
<td>22</td>
<td>100</td>
<td>21</td>
<td>0.03</td>
<td>0.96</td>
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<tr>
<td></td>
<td></td>
<td>23 Sep.</td>
<td>19 Nov.</td>
<td>bags</td>
<td>5/5</td>
<td>28</td>
<td>79</td>
<td>14</td>
<td>0.1</td>
<td>0.5</td>
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<tr>
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<td>19 Nov.</td>
<td>nets</td>
<td>25/25</td>
<td>1,224</td>
<td>100</td>
<td>2</td>
<td>1.8</td>
<td>0.002</td>
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<td></td>
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<td>19 Nov.</td>
<td>bags</td>
<td>5/5</td>
<td>4,392</td>
<td>N/A</td>
<td>637</td>
<td>15.7</td>
<td>0.15</td>
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<tr>
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<td>22 Oct.</td>
<td>19 Nov.</td>
<td>nets</td>
<td>25/10</td>
<td>111</td>
<td>94</td>
<td>1</td>
<td>0.4</td>
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<td></td>
<td></td>
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<td>19 Nov.</td>
<td>bags</td>
<td>5/5</td>
<td>203</td>
<td>99</td>
<td>44</td>
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<td>19 Nov.</td>
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<td>2</td>
<td>0.3</td>
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<td>19 Nov.</td>
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<td>99</td>
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<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
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<td></td>
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<td>19 Nov.</td>
<td>bags</td>
<td>5/5</td>
<td>223</td>
<td>97</td>
<td>26</td>
<td>0.8</td>
<td>0.12</td>
</tr>
</tbody>
</table>
the west breakwater site, the fry CPUE on the west breakwater was about 8× higher than at NR1 (mean 0.21 fry/device/day at WWF vs. 0.026 fry/day at NR1; $F_{0.05}(2), 1, 165 = 5.86, P < 0.017$, Tukey test). In the old-design fry traps, 1997 fry CPUE was indistinguishable among WWF, WWU, and NR1 (pooled mean 0.02 fry/device/day; $F_{0.05}(2), 2.85 = 0.68, P > 0.50$). In new-design traps, however, CPUE was approximately 6.4× higher at NR1 than at the mean of the west breakwater sites, which were indistinguishable from one another (NR1 mean 0.16 fry/device/day, pooled WWF, WWU mean 0.025 fry/device/day; $F_{0.05}(2), 2.74 = 8.16, P < 0.001$, Tukey test).

### Laboratory Egg Incubation

Incubators in the crib with clean cobble contained an average of 7.7 live sac fry (SD = 1.0; survival = 15%), in the crib with zebra mussel-fouled cobble there were an average of 9.8 live sac fry (SD = 4.7; survival = 20%), and in the control incubators there were 6.2 fry (SD = 2.5; survival = 12%); there was no statistically significant difference between the treatments. The remaining eggs in each incubator were dead.

### DISCUSSION

Several studies have demonstrated that spawning lake trout are attracted to artificial reefs (Marsden 1994, Marsden et al. 1995, Fitzsimons 1995, Schreiner et al. 1995), but little work has been done to evaluate these structures as a potential management tool for lake trout restoration. If artificial reefs enhance lake trout reproductive success by providing spawning substrate, then artificial reefs could fulfill a dual purpose, serving a human need as well as enhancing eventual restoration of lake trout. New construction or renovation of breakwaters, for example, can require relatively little modification to make portions of the structure useable by spawning trout. Several plans were considered for the Port of Indiana breakwater rehabilitation, of which the submerged reef design was considered to be at least as effective as the rest, with the added benefit of potentially encouraging trout spawning. The only constraint imposed by this dual function design was considered to be at least as effective as the rest, with the added benefit of potentially encouraging trout spawning. The only constraint imposed by this dual function design was modification of the construction schedule to accommodate the lake trout spawning schedule. Construction was scheduled from late spring to early fall of each year in order to avoid impacting lake trout spawning or egg hatch. This was only necessary because construction took place on an existing spawning site, and would not necessarily be an issue for a new project. However, post-construction evaluation is critical for the design of artificial spawning reefs, to ensure that fry are successfully produced. If lake trout are drawn away from natural spawning reefs where egg and fry survival is high to spawn on artificial reefs where egg and fry survival is low, then such reefs become “attractive nuisances.” In other words, they attract lake trout, but may not enhance production.
One of the primary disadvantages of breakwaters and intake structures as spawning substrates is that they are, of necessity, in shallow water and close to shore. Structures intended to serve only as artificial reefs are usually also constructed in shallow water, in part due to logistical problems with construction in deep water (e.g., dumped materials tend to scatter more widely when deposited in deep water; visual assessment of the reef structure becomes more difficult in deep water). Shallow structures are vulnerable to wave energy, produced by severe fall and winter storms, which may damage eggs (Eshenroder et al. 1995). Fish which are attracted to shallow structures become highly accessible to fishermen, though fishing mortality on lake trout has or can be regulated by seasonal fishing restrictions. The habitat requirements for post-emergent fry are not well understood, but such habitat may be distant from shallow, near-shore reefs. Shallow reefs are inhabited by a higher density and diversity of potential egg and fry predators than deep reefs, including a number of exotic species such as alewife, carp, and round gobies (Krueger et al. 1995, Marsden 1997, Chotkowski and Marsden 1999). Most of the shallow reefs in the Great Lakes also are now fouled to some extent by zebra mussels.

In this study, both the attractiveness and effectiveness of an artificial reef as a lake trout spawning site were examined. The new substrate and submerged reefs added to the Port of Indiana breakwater were highly successful as an attractant for spawning lake trout. Egg deposition in nets and traps ranged from 0.01 to 1.4 eggs per trap or net day; other studies using the same gear on natural sites reported a CPUE of 0.02 to 2.33 in Lake Ontario (Marsden and Krueger 1991), and 0 to 0.02 in Lake Michigan (Marsden 1994). In a review of collections in traps throughout the Great Lakes, CPUE ranged from 0 to 0.5 (Schreiner et al. 1995). Perkins and Krueger (1995) report 32 to 688 total eggs and chorions collected in individual egg bags between September and December, compared with 5 to 1,564 eggs plus chorions collected per bag between September and November in this study. Construction on the west breakwater and the first new submerged reef was completed in late October, 1995; the following spring lake trout fry were emerging from the reef. The second reef was completed in late October, 1996, and by 19 November 1996, when the egg collection devices were first lifted, lake trout had already spawned on the new site. Spawning activity on the new reefs, as measured by egg CPUE, was similar to that on the existing west breakwater. The bathymetry around the breakwater and the new reefs was flat, and consisted of sand/silt substrate, and the new reefs were over 1 km from the existing west breakwater substrate where lake trout spawned prior to the new construction. Therefore, lake trout must have searched for and been attracted to the new spawning substrate, despite previous familiarity with and use of an adjacent spawning area at the west breakwater. A similar conclusion was drawn from previous work in which lake trout spawned on experimental reefs constructed 80 m from a natural spawning reef (Marsden et al. 1995). These results indicate that it is possible to build a reef which will attract spawning lake trout, and that spawning will occur almost immediately, i.e., within a year of construction. The availability of the new reefs did not appear to detract from spawning at the old west breakwater site; egg CPUE on the west breakwater did not decline in 1995 or 1996 as new areas of cobble became successively available. This suggests that artificial reefs do not simply draw spawning fish from surrounding areas, but could increase production.

An artificial reef can only be considered successful if it increases reproductive success over that which occurred in the area prior to construction. Prior to construction of the original breakwater at the Port of Indiana, no spawning was likely to have been successful in producing fry, if it occurred at all. The substrate in the immediate area, and probably for many square miles around, is sand and silt. Even if lake trout deposited eggs, predators would have immediate access to them. Goodyear et al. (1982) cited an observation of “windrows” of eggs along the Indiana dunes shoreline (3 km east of the Port of Indiana) which illustrates an alternate fate of eggs spawned on sand. It appears that the original breakwater created a spawning habitat where there was none present. However, the site does have all the potential problems mentioned earlier—high wave energy, a number of resident or visiting native and exotic egg predators, fishing pressure, and also a lack of nearby nursery habitat for emergent fry (though the exact nature of nursery habitat for lake trout is not well described). The effect of wave energy at this site on lake trout eggs is difficult to evaluate quantitatively. Any north wind with a westerly component tended to generate 1 to 5 m waves at the breakwater, and damage to the breakwater was clearly visible. Fishing pressure at the site is difficult to assess quantitatively, as there are
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no estimates of adult density in fall, and catch data are limited to a creel survey which ends on 31 October. There is a daily bag limit of two fish and no closed season, and fishermen are aware that lake trout are congregated at the breakwater. During the field work 1 to 3 fishing boats were observed in the area; the fishing pressure may not have had a large effect on the spawning population. Potential predators of lake trout egg and fry at the site included sculpin, yellow perch, crayfish, and the exotics carp and alewife. Among the 224 sculpin and 363 alewife that were collected by trawl, only one sculpin contained fry. These results suggest that predation may not be sufficiently heavy to limit successful reproduction by lake trout at the site. However, the appearance of round gobies on the breakwater in 1997 poses a potential future threat to egg survival, as gobies readily consume lake trout eggs in laboratory experiments (Chotkowski and Marsden 1999). The issue of post-emergent fry survival cannot, at this time, be addressed. The south end of Lake Michigan, adjacent to the Port of Indiana breakwater, slopes very gradually and appears to be largely sand/silt substrate until the Indiana Shoals, approximately 30 km distant. It is therefore likely that refugia and possibly food for post-emergent and older fry are lacking. It can be concluded that, prior to the arrival of zebra mussels, the Port of Indiana breakwater enhanced lake trout reproductive success to the fry stage in southern Lake Michigan. However, zebra mussels appear to have a strong negative effect on spawning activity and egg survival. Egg deposition was highly reduced on substrates fouled by zebra mussels, relative to clean substrate. These data suggest that adult lake trout reject spawning substrate fouled by zebra mussels. This rejection may be based on ability of the trout to detect poor water quality in the immediate vicinity of the mussels, or some other factor such as the change in the physical appearance of zebra mussel encrusted substrate. Water quality degradation has been measured within zebra mussel colonies in laboratory studies, with significantly increased nitrate and decreased oxygen concentrations at the base of the zebra mussel colony (Call 1996); however, no studies have examined changes in substrate interstitial water quality in the presence of zebra mussels. Water quality is likely to be degraded directly, due to oxygen consumption and waste production by zebra mussels, and indirectly, by production of biological oxygen demand due to degradation of feces and pseudofeces. Lake trout eggs could also be suffocated by accumulation of fecal and pseudofecal material in the substrate.

Survival of eggs after spawning was also negatively affected by the physical presence of zebra mussels. The proportion of dead eggs was low at all sites in all years compared with other studies (e.g., Perkins and Krueger 1995), though it was highest on west wall fouled substrate. However, egg mortality can result from handling after capture. Therefore the number of chorions was used as an indicator of damage that must have occurred in situ. The number of chorions, relative to whole eggs, found on fouled substrates was significantly higher on fouled than clean substrate. It is possible that wave-induced movement of eggs over the shells of zebra mussels caused sufficient abrasion to break chorions. In addition, 42 eggs and 70 chorions were found in a carp stomach in 1993 (Marsden 1997). Under normal circumstances it is unlikely that a carp would have access to eggs which had settled into interstitial spaces. The dense colonies of zebra mussels likely occluded the interstices to the extent that lake trout eggs were unable to penetrate them. The higher catch of eggs in egg bags than egg nets is likely due to disturbance of the zebra mussel colonies during egg bag burial, so that interstices within the egg bags were relatively unobstructed. Eggs trapped on the surface of the substrate would be vulnerable both to predation by large-bodied fishes, and movement by localized currents. The abundance of zebra mussels at the site may have attracted feeding carp, and may now attract round gobies, as both species forage on the mussels. The presence of zebra mussels appears to increase predator access to lake trout eggs, and may increase the local density of lake trout egg predators.

Contrary to expectations based on egg collection data, fry hatch was similar on fouled and unfouled substrates in the laboratory and on the breakwater. Fry captures were also highly variable; for example, catches per unit effort ranged from 0.8 to 20.8 per year on the fouled west breakwater. These figures suggest that fry traps may not be highly reliable capture devices for quantitative studies of fry abundance. Fry appear to move readily above and possibly within the substrate within days of hatching (Baird and Krueger 2000). Fry could therefore have moved between the fouled and unfouled west breakwater substrates prior to catch. Fry also may be more vulnerable to capture on fouled substrates than clean, due to their inability to move back into interstices on fouled substrates. Alternatively, zebra
mussels may enhance incubation of eggs that survive abrasion and predation, and are able to penetrate into the substrate interstices. Under controlled conditions in which fry were trapped in incubators in raceways, fry hatch was similar between fouled and unfouled substrates. These data suggest that the assumptions about the interaction between zebra mussels, interstitial water quality, and egg incubation may be incorrect, and need to be studied further. However, the survival to hatch in the laboratory incubators was low compared with other studies (e.g., 76 to 86%, Eshenroder et al. 1995, 88%, Manny et al. 1995). The cause of this low survival is unknown, but may have masked any differences between experimental treatment and controls. Further use of incubators, including in situ studies, is recommended to elucidate the effect of zebra mussels on egg incubation.

Management Implications

This study demonstrates that lake trout are highly attracted to new substrates, and that it is possible to construct underwater structures with dual functions, e.g., as spawning reefs and breakwaters. However, such reefs are potentially vulnerable to a number of biotic and abiotic hazards which reduce spawning success. All reefs, natural and artificial, within approximately 20 m of the surface in the Great Lakes are now highly vulnerable to zebra mussel colonization. Zebra mussel colonies discourage adult lake trout from spawning, damage eggs, and increase egg vulnerability to large-bodied predators. The ultimate effect of zebra mussels on egg hatching is still in question. Whereas artificial reefs had a high potential as a management tool to improve lake trout spawning prior to the introduction of zebra mussels, they are of little use while zebra mussel densities remain high. Artificial reefs may be a fatal attraction, insofar as lake trout are stimulated to use them while the substrate is clean, and then continue to use them en lieu of better areas after colonization by zebra mussels has taken place. Perhaps management for lake trout restoration should emphasize use of deepwater (> 20 m) spawning sites, including stocking of putative deepwater strains and possible construction of artificial reefs in deep water. Also note, however, that while sites below 20 m may be colonized by zebra mussels at lower densities than shallow sites, colonization by quagga mussels may be heavy (Mills et al. 1996).

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