Potential impacts of clearcut logging on lake trout (*Salvelinus namaycush*) reproduction in northwestern Ontario lakes.

by

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ABSTRACT

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Lake trout reproductive habitat was characterized in three small lakes, 250 km northwest of Thunder Bay, Ontario, by measuring the physical characteristics of preferred spawning habitat including 1) depth, 2) substrate size, 3) interstitial space depth, 4) organic material abundance, 5) embeddedness, 6) particulate debris, and 7) permeability. Principal Components Analysis indicated that periphyton, macrophyte, and particulate debris abundance all increased with shoal depth, while substrate size decreased. Hydraulic permeability, indexed by the erosion of gypsum cylinders, was higher in coarser substrates. Lake trout egg deposition density in egg traps averaged 70 eggs m^{-2}, of which 45% were viable by late fall. Lake trout embryo survival and emergence in enclosures varied with Fredle Index, and was highest (75%) in cobble/rubble mixtures. Fine sediment which was added to incubators in the fall was absent when the incubators were retrieved in the spring. At the single fine sediment dosage tested in this study (equivalent to a layer approximately 2.5 cm deep across the surface of each incubator), lake trout hatching success was not significantly affected. Although experimental nutrient enrichment (P and N) of a spawning shoal increased periphyton biomass by 2.5 times over the summer, the effects of this on reproductive habitat are not known at present.

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I express thanks to my friends for their continued efforts to try and find lake trout exciting. I am truly grateful to Stephen for his ongoing encouragement and genuine enthusiasm about my work.

I am forever thankful for my family's unconditional love and support. Thank you Marsha, for helping me find humor during the frustrating times, and Amy for sharing your strength and determination. This thesis, and everything it represents, is dedicated to my parents. To my Father who encouraged me to follow my dreams and in memory of my Mother who instilled in me the faith to truly believe in myself. The influence of these extraordinary individuals has allowed me to envisage what I strive everyday to become.

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INTRODUCTION

CONTEXT OF STUDY

Interactions between water, soil, and vegetation within a watershed are primarily responsible for allochthonous nutrient and sediment contributions to lake basins (Likens 1984; Bormann and Likens 1985). Therefore, alteration of riparian communities by clearcut logging (and road construction and maintenance activities), may have significant impacts on a lake (Smol *et al.* 1983; Jaakko 1991). For example, sediment and nutrient loading have repeatedly been documented for both stream and lake systems following timber harvesting (Likens *et al.* 1970; Burns 1972; Posey 1973; Pennington 1981; Hornbeck and Kropelin 1982; Vitousek;1983; Ward 1992). Based on the experimental work conducted in the Hubbard Brook Experimental Forest and other locations, Likens (1984) suggested that the changes which would typically occur in a watershed ecosystem following deforestation would include a) more erosion and transport of particulates into a lake, b) increased concentrations of phosphorus and suspended solids in water, and c) generally a more eutrophic (nutrient and organic material enriched) lake.

There is a growing concern regarding watershed disturbance and the subsequent habitat degradation threats to the lake-trout stocks throughout Ontario (Evans *et al.* 1991). Lake-trout lakes exhibit a narrow range of limnological characteristics (e.g. depth, temperature, dissolved oxygen and solids, nutrients, pH, and are thought to be vulnerable to even slight changes in water quality or land use (Ryder and Johnson 1972; Ryan and Marshall 1996). Lake trout in many small northern lakes typically spawn in shallow (<2m)

nearshore areas with clean coarse substrate; locations which are in close proximity to any potential disturbances resulting from shoreline modifications (McAughey and Gunn 1995).

USE OF SPAWNING SHOALS BY LAKE TROUT

Lake trout reproductive habitat exhibits distinct characteristics required to facilitate development of eggs through to early larval stages (Olver *et al.* 1991), and may have an ecological role far more important than suggested by shoal size alone (Steedman and Regier 1987). Lake trout have demonstrated their ability to respond rapidly to spawning habitat loss in Whitepine Lake (Sudbury, Ontario) by selecting new sites when their preferred habitat has been altered (McAughey and Gunn 1995). However, egg deposition does not necessarily indicate that the fish have selected sites suitable for embryo incubation and emergence. Spawning habitat quality can be defined by both the intensity of use by spawners, and by the degree of successful incubation of deposited eggs to hatching, and survival of fry to emergence. Therefore, the evaluation of spawning and incubation habitat quality requires an understanding of the factors that affect adult choice, egg incubation and fry survival (Marsden *et al.* 1995a).

In Ontario, lake trout spawn in the fall (late September to mid-November), in water temperatures ranging from 8.9 to 13.9°C (Scott and Crossman 1973; Sly and Widmer 1984). These declining temperatures are usually accompanied by a reduced photoperiod and strong on-shore winds (Martin and Olver 1980). Lake trout are nocturnal spawners which makes observations of spawning behaviour difficult (Gunn 1995).

Inland lake-trout usually spawn in shallow water (1-4 m) along shorelines, or shoals that are exposed to prevailing winds of sufficient magnitude (wind fetch >0.5) to keep the area swept clean of silt and particulate debris (Martin and Olver 1980; Palilionis 1981; Sly 1984; Nester and Poe 1987; Evans *et al.* 1991; Gunn 1995). Unlike most salmonids, lake trout do not build nests or redds (Martin and Olver 1980; Moyle and Cech 1988), but broadcast their eggs over scattered piles of clean broken cobble (2 - 62 mm) and rubble (65 - 256 mm) substrate, interdispersed with larger boulders (Martin and Olver 1980; Evans *et al.* 1991). Small patches (0.25 - 5 m^2 surface area) of gravel or small rubble were the focus of lake trout spawning activity in a 60 ha inland lake in north central Ontario (Gunn 1995).

The eggs usually fall into the substrate interstices (spaces between substrate pieces), where they absorb water, swell, and become wedged within the substrate. These interstices, (usually 20-30 cm deep) entrap the eggs, protecting them from physical disturbance and predators (Edsall *et al.* 1992). Substrate stability is important to embryo survival, and spawning habitat is usually not located on actively moving beach or gravel channels (Sly and Schneider 1984).

The growth, development, and survival of lake trout eggs and larvae are influenced by the physical and chemical characteristics of the surrounding environment. Lake trout embryos require an ample supply of oxygenated water which is free of toxic substances (McNeil and Ahnell 1964). Development and survival of salmonid embryos are adversely affected if dissolved oxygen drops below 6 mg/L (Phillips 1971; OMNR 1984).

Salmonid embryo survival and fry emergence have a positive relationship with mean substrate particle size and permeability (intragravel water exchange) and a negative

relationship with increasing abundance of fine sediment (McNeil and Ahnell 1964; Chapman 1988; Petticrew and Kalff 1991). Chronic or intense sediment loading can bury rock and gravel substrate making it unavailable to spawning fish (Francis *et al.* 1979). Less intense sedimentation can fill interstitial spaces, preventing eggs from penetrating the substrate layers, and increasing the egg's susceptibility to predation by fish and invertebrates. Increases in fine sediment, and a subsequent decline in substrate permeability, may impair the ability of water currents to mix freely and deliver oxygen to, and remove waste products (*i.e.* NH_4^+, CO_2) from incubating embryos (Chapman 1961; Phillips 1971; Ward 1992). Reiser and White (1988) confirmed that for steelhead and chinook salmon eggs, the smaller sediments (< 0.84 mm) were most detrimental to incubating eggs. Fall chinook-salmon eggs suffered as much as 85% mortality when 15-30% of the voids in the gravel beds, in Abernathy incubation channels, were filled with sediment (Shelton and Pollock 1966). Sediments can also form a barrier to fry emergence (Phillips 1971).

Cultural (anthropogenically accelerated) eutrophication has been identified as the causative factor of increased algae growth on lake-trout reproductive habitat in Lake Ontario (Ryder and Edwards 1985; Sly 1988). Plant and algae debris can be trapped and accumulate in the substrate of spawning sites when there are high nutrient levels originating from shoreline disturbances (Evans *et al.* 1991). Algae and periphyton, like fine sediment, may impede an embryo's ability to penetrate the interstices, and increase embryo susceptibility to predation. In addition to the clogging of interstitial spaces, decomposition of organic material could result in oxygen loss or elevated NH_4^+ within the

incubating environment. In severe cases, oxygen can be depleted to a level insufficient for a developing embryo to survive (Sly 1988).

Spawning behavior and habitat of lake trout have been studied by mapping historical reproductive habitat, egg collections, visual assessment of spawning grounds, and substrate analysis. Most substrate surveys and analysis visually assess the uppermost layer of substrate to determine the particle-size distribution at a location of interest. These methods are not reliable for certain sediment mixtures, and significant information is often lost when only the dominant substrate is recorded (Bain *et al.* 1985). These substrate assessments do not adequately describe the material below the surface, the substrate which eventually becomes the incubating habitat for the lake-trout embryos.

Unfavorable weather conditions associated with fall spawning and early spring fry emergence are most likely responsible for the lack of research regarding the incubation and emergence of lake-trout fry. Many studies have attempted to investigate the relationship between the embryo incubating environment and fry emergence. However, lake-trout fry typically emerge when lakes are still ice covered, making quantitative measurements of fry production difficult, and researchers have often resorted to the deployment of a variety of egg-incubating devices in the fall. Manny *et al.*(1989) placed fertilized lake-trout eggs in individual compartments of Plexiglass incubators (25 x 12.5 x 1.5 cm) that were buried by SCUBA divers in rock rubble, and left over the winter. These incubators have since been used in a number of reproductive habitat quality studies (Eshenroder 1988; Edsall *et al.*1992). However, upon burial of these and similar incubating devices, the embryos are not being subjected to an entirely natural incubating environment. By creating an artificial microenvironment, factors such as substrate

permeability and subsequent water exchange no longer have a direct effect on the developing embryo. To measure the relationship between the physical nature of the reproductive habitat, and embryo survival and emergence, experimental containers should accurately simulate a natural incubation environment.

STUDY OBJECTIVES

Figure 1 provides a conceptual framework of the land-water linkages relate to lake trout spawning shoal habitat and subsequent reproductive success. The goal of this study was to gain a further understanding of the characteristics of lake trout reproductive habitat and success by measuring or manipulating the elements highlighted in Figure 1.

This thesis attempts to identify and quantify the habitat variables that characterize undisturbed lake trout spawning shoals in three small lakes in north-western Ontario. It then attempts to determine how some of these habitat variables could be limiting or regulating lake trout reproductive success by testing the null hypothesis that embryo hatching success is not significantly effected by substrate size and composition. To investigate the potential impacts that timber harvesting practices may have on lake trout reproductive habitat (*i.e.* siltation and nutrient enrichment) and subsequent lake trout embryo survival, I tested two additional null hypotheses: a) the deposition of fine sediment has no significant effect on lake trout embryo hatching success, and b) increased P and N water concentrations have no significant effect on periphyton accumulation and abundance on lake trout spawning substrate.

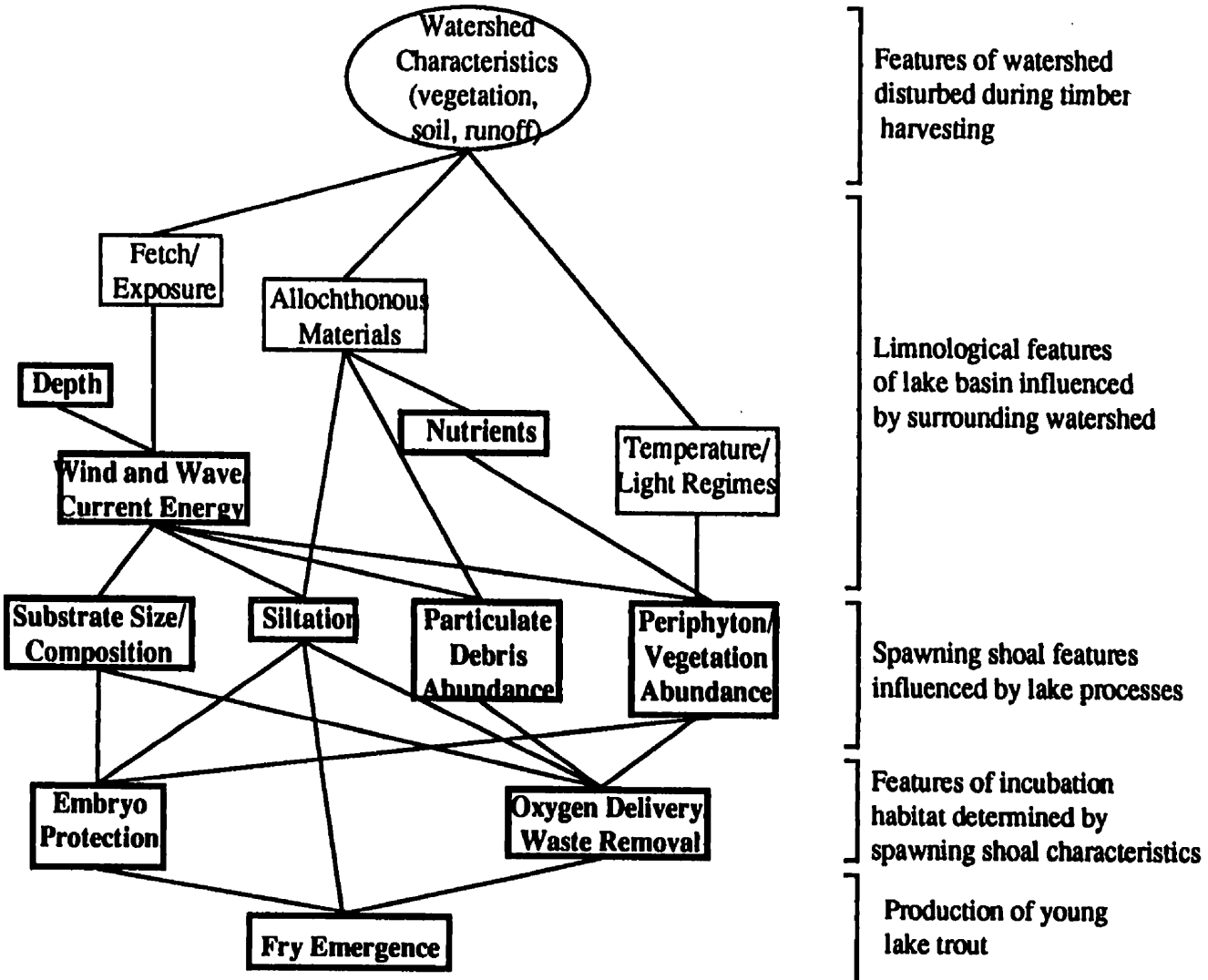

Figure 1. Schematic diagram illustrating the various factors of the watershed and lake basin which may, influence the abiotic and biotic characteristics of spawning shoals, and subsequent lake trout reproductive success. Highlighted factors were measured or manipulated in this study

METHODS

STUDY AREA

This study was undertaken in Lakes 20, 26, and 42 at the Coldwater Lakes experimental watersheds, located on the Canadian Shield about 200 km northwest of Thunder Bay, Ontario, Canada, in the transitional zone between the Great Lakes - St. Lawrence forest and the boreal forest (Figure 2). The Coldwater Lakes research project was initiated in 1990 to measure the effects of logging on lake ecosystems, and test the effectiveness of shoreline buffer strips in preventing those effects (OMNR 1996). The lakes are small, oligotrophic headwater basins characterized by sparse fish faunas (Table 1; France and Steedman 1996). Lakes 20, 26, and 42, have similar fish community compositions. Lake trout and white sucker (*Catostomus commersoni*) are the only two large-fish species present (Table 1; Appendix I).

Lake trout spawning shoals were identified in the fall of 1993 and 1994, by OMNR staff using snorkeling gear, who placed permanent coloured markers in the areas where lake trout egg deposition was observed. These surveys resulted in the identification of one major spawning shoal within each study lake.

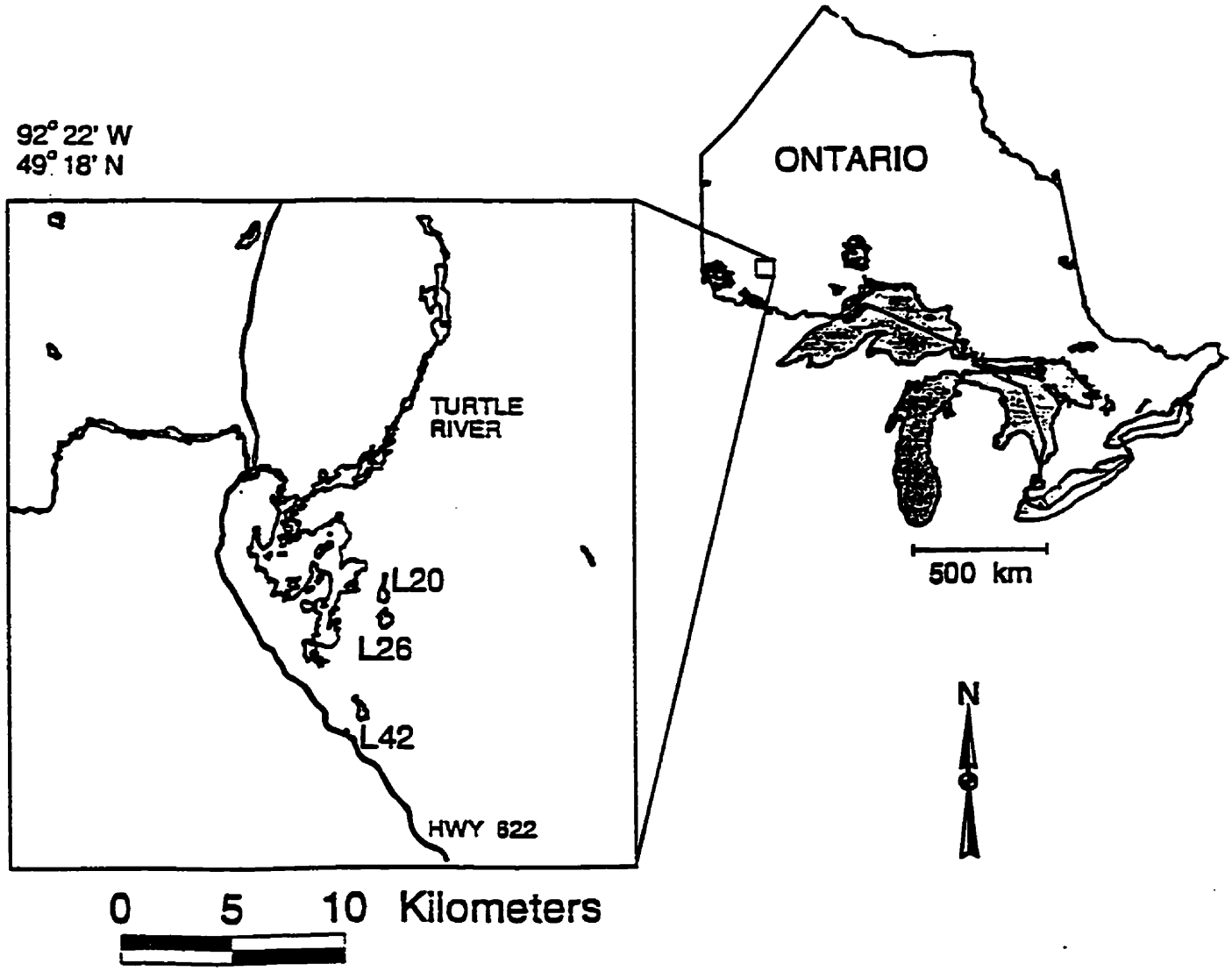

Figure 2. Map of the study lakes 20, 26, and 42.

Table 1. Characteristics of the study lakes. Chlorophyll a, Secchi depth, and pH are 1992-1993 averages. Littoral fish species are coded as follows: white suckers *Catostomus commersoni*, 1; northern redbelly dace *Phoxinus eos* and finescale dace *Phoxinus neogaeus*, 2; common shiners *Luxilus cornutus*, 3; blacknose shiners *Notropis heterolepis*, 4; fathead minnows *Pimephales promelas*, 5; pearl dace *Margariscus margarita*, 6; brook stickleback *Culaea inconstans*, 7; Iowa darters *Etheostoma exile*, 8; and slimy sculpins *Cottus cognatus*, 9 (France and Steedman 1996).

Lake Characteristics	Study Lake		
	20	26	42
Lake area (ha)	57	27	28
Maximum lake depth (m)	32	37	19
Chlorophyll *a* (*ug*/L)	3.0	0.9	1.3
Secchi depth (m)	3.1	5.0	4.2
pH	6.8	7.1	6.7
Littoral fish species	1-9	1, 2, 4-9	1, 2, 5-7, 9
lake trout population estimate[1]	196-218	256-369	129-177

[1] Lake trout population estimates for the study lakes are based on fall gill netting data obtained in 1992-1993 for Lake 20, 1992 and 1995 for Lake 26, and 1992-1994 for Lake 42. (OMNR unpublished data)

PHYSICAL ATTRIBUTES OF LAKE TROUT SPAWNING SHOALS

Sample Sites

Random selection methods used throughout this study are summarized in Appendix II. The permanent markers used for the MNR egg deposition surveys were used to determine the outer perimeter of each of the three spawning shoals. Within each spawning shoal, 20 sampling sites were randomly selected and marked with a coloured and numbered rock. These markers established the center of a 42 cm diameter plot for each of the 20, 16, and 20 sample sites for the shoals in Lakes 20, 26, and 42 respectively. The depth of the sample site from the water surface was measured to the nearest cm.

Periphyton

Relative periphyton abundance on shoal substrate (none, low, medium, high) was visually assessed using the criteria presented in Appendix III, and included attached algae, organic detritus, and some fine sediment (Wetzel 1979).

Vegetation and Particulate Debris

Macrophyte (submerged aquatic vegetation), and particulate debris (*i.e.* sticks, bark, wood pieces, leaves) abundance were visually estimated as the percent of the total sample plot area covered (Appendix IV).

Embeddedness

Embeddedness describes the extent that the larger particles (boulders, rubble, or gravel) are covered by fine sediment (Platts *et al.*1983). The relative embeddedness of the

substrate (none, low, medium, of high) was assessed using the criteria presented in Appendix V.

Interstitial Space Depth

At each sample plot, ten interstitial spaces were randomly selected. A suspended lead shot with a diameter of 4 mm (simulating that of a non-waterhardened lake trout egg) was lowered into each of these spaces until the shot reached its maximum possible depth. With the line remaining taut, the penetrated depth was measured relative to the average surface level of the substrate surrounding the interstitial space.

Substrate Size and Composition

Substrate size and composition were quantified using the technique described by Marsden and Krueger (1991). At each sampling site, divers removed 10 L of substrate from the area beneath a 42 cm diameter circular frame. Efforts were made to include fines (sand) in the sample; however some loss was unavoidable. On shore, the substrate was washed through a series of sieves, dividing the material into five possible diameter size classes: fines (0-6.3 mm), gravel (6.4-75.9 mm), cobble (76.0-149.9 mm), rubble (150.0-303.9 mm), and small boulders (304.0-609.9 mm) (Platts *et al.* 1983). For each sample site, the material within a size class was collected and placed in a plastic container with a known volume of water. Volumetric displacement was used to determine the volume of each size class.

Substrate Permeability

Fredle Index

Fredle Index describes the particle size distribution in sediment mixtures, and is calculated as follows.

F_i = Fredle Index = $\frac{D_g}{S_o}$

where D_g = geometric mean particle size

S_o = sorting coefficient = $\frac{d_{75}}{d_{25}}$

The S_o is derived by taking the square root quotient of the grain size at the 75th percentile divided by that at the 25th (Lotspeich and Everest 1981).

The Fredle numbers index both pore size and relative permeability, both of which increase as the index becomes larger. The Fredle Index was calculated for each sample site using volumetric substrate abundance described above. Fredle Indicies were divided into four index classes: Class 1 (0-50), Class 2 (51-100), Class 3 (101-150), and Class 4 (151-200) (Figure 3).

Indexing Water Circulation Above and Within Spawning Shoals

I used gypsum cylinders to measure the water turbulence occurring above each of the three spawning shoals and within various substrate types.

Preparation of Gypsum Cylinders

Blocks of hydrated calcium sulphate (gypsum or Plaster of Paris) have been used as qualitative and quantitative water turbulence (disturbance, flow) sensors in both marine and freshwater systems, and can be used as an inexpensive measure of average current speeds. For this study gypsum cylinders were prepared and calibrated according to Petticrew and Kalff (1991), and R. Kushneriuk (pers. comm.). A mixture of Plaster of

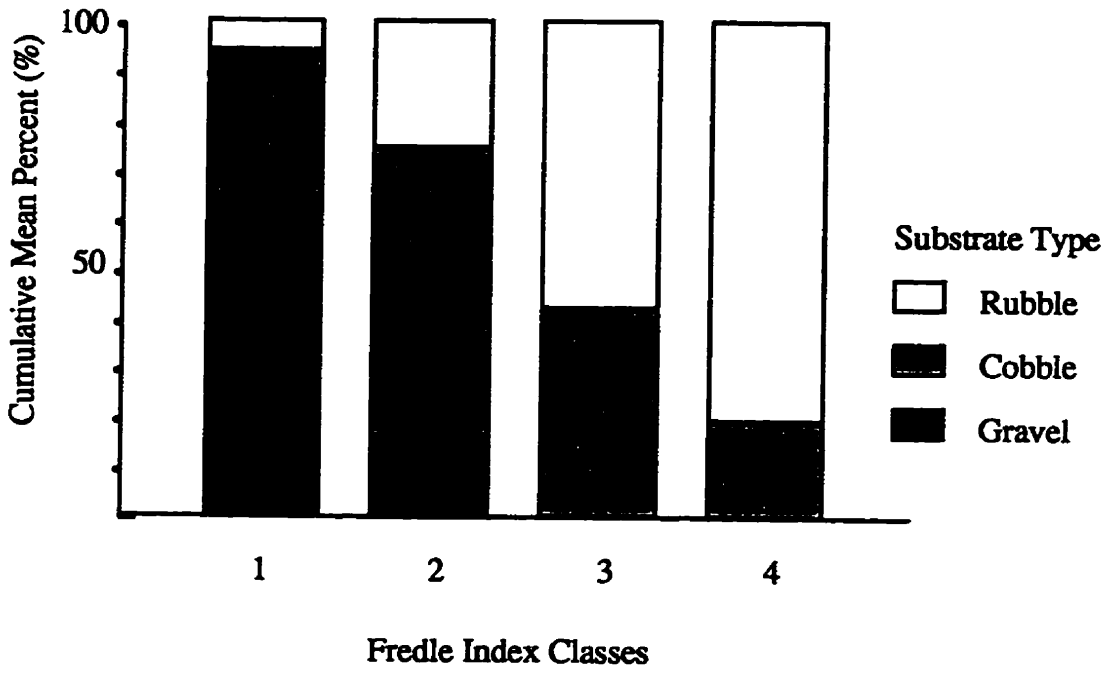

Figure 3. Relationship between Fredle Index Class and particle size distribution for spawning shoal substrate samples analyzed in this study

gypsum and water were poured into cylindrical molds (9.5 cm long x 2 cm diameter) and left to set at room temperature overnight. A 16 cm long nylon cable tie was inserted into each cylinder before the mixture hardened. The cylinders were removed from the molds and oven dried at 40°C for a minimum of 3 hours. The ends of each cylinder were sealed with an oil-based paint to restrict erosion to the circumference of the cylinder. Each cylinder was numbered on the protruding end of the nylon tie. All cylinders used in this study were made from the same batch of gypsum.

Calibration of Cylinder Diameter Loss to Water Flow

A 45 cm wide recirculating flume channel, with a water depth of 15 cm and a temperature of 16-18°C, was used to calibrate the cylinders. A paddle wheel, powered by an electric motor, created the water flow. Water velocities in the flume were calculated as the mean velocity (n=5) of a small piece of styrofoam as it traveled the length of the flume. Water velocity was set between 0 and 12 cm sec^{-1}. For each run, four to eight gypsum cylinders were vertically submerged mid-depth across the width of the channel. The cylinders were left in the flume for up to 36 hours, removed, oven dried at 40°C, and re-weighed. To avoid problems of saturating the flume water with gypsum, the flume was drained between runs.

Due to the number of cylinders required for field deployment, it was necessary to reuse partially eroded cylinders. Cylinders with a smaller radius and surface area have the potential to erode at a slower rate than larger cylinders. Therefore, cylinder diameter loss was explored as a possible index of water flow. The volume (measured using volumetric displacement) of randomly selected cylinders of various weights was used to calculate the

cylinders' density. After confirming that there was no significant relationship between cylinder weight and density (Appendix VI), cylinder diameters were calculated as follows:

$$\text{Diameter} = 2 (V / (3.14 L)^{1/2}$$

where: V(volume) = mass / density
L = length of cylinder

Linear regression indicated that there was no significant relationship between cylinder weight and diameter loss rate (r^2 =0.00, ρ =0.91, n =286). Therefore cylinder diameter loss rate was used to resolve the cylinders' response to water flow. Linear regression analysis of the flume data indicated a positive linear relationship between cylinder diameter loss rate and water velocity (Figure 4). The position of the cylinder in the flume did not appear to affect the diameter loss, as illustrated by the minimal variation exhibited by replicate cylinders.

Cylinder Deployment

At each shoal, at least five sites were randomly chosen from among the previously established sample sites. At each site, one cylinder was suspended 20 cm above the substrate (with a weight and float system) and another cylinder was buried under one layer of substrate (Figure 5). Between July 24 and September 7, 1995, cylinders were deployed for at least two sampling intervals of up to 72 hours. Diameter loss rate was estimated from weight loss for each deployment interval. To estimate sampling variation in various substrate sizes, three cylinders were buried together for 24 hours at five sites on the Lake 26 shoal on August 7, 1996. The permeability of the substrate was indexed as follows:

$$\text{Permeability (\%)} = \frac{\text{cylinder diameter loss rate within the substrate}}{\text{cylinder diameter loss rate above the substrate}} \times 100$$

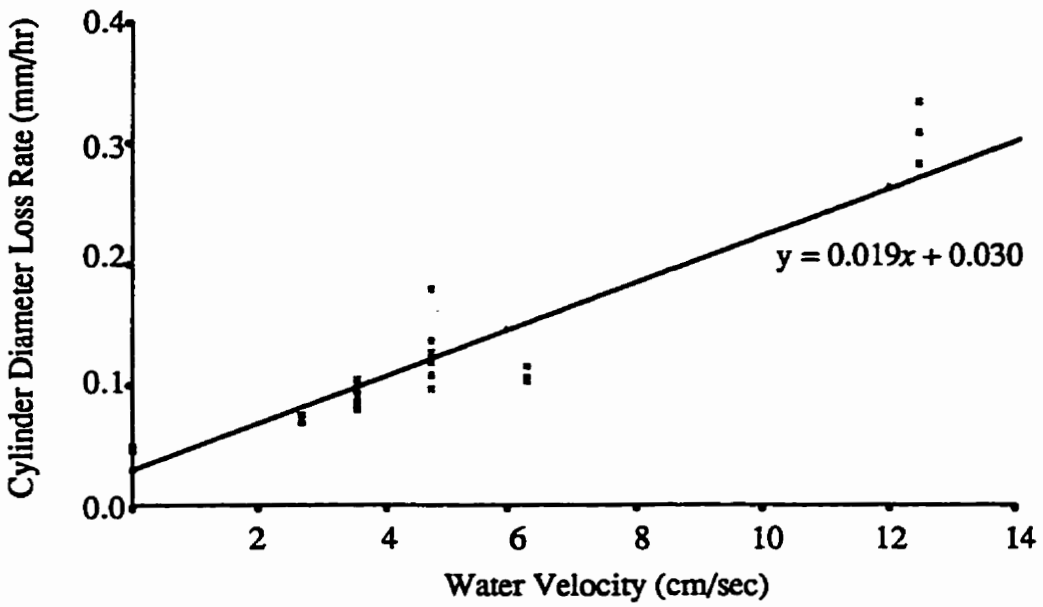

Figure 4. Relationship between cylinder diameter loss rate and water velocity for cylinders calibrated in recirculating flume. The linear relationship is significant (r^2=0.86, p=0.000, n=32).

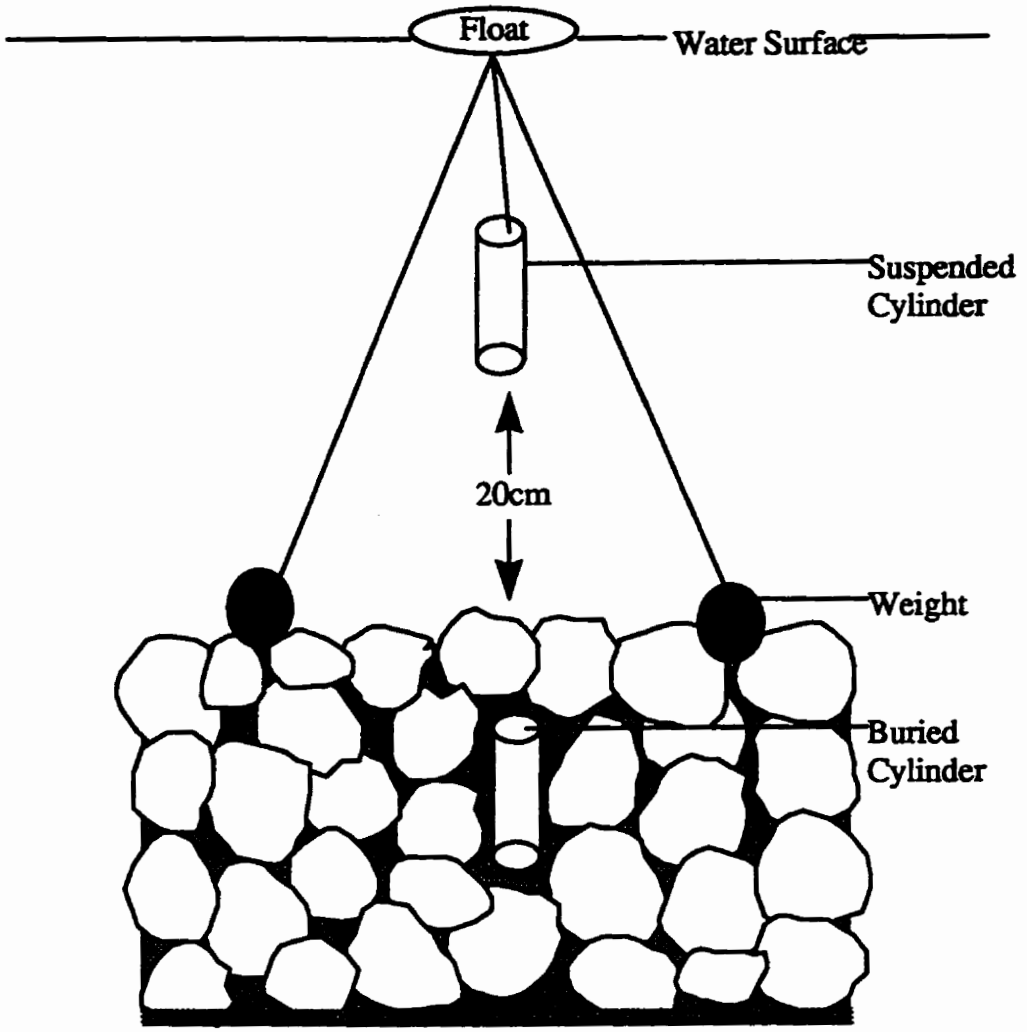

Figure 5. Water flow measurement using gypsum cylinders within and above shoal substrate.

EGG DEPOSITION

Egg traps (615 cm^2 surface area) were constructed of 5 cm-wide rings cut from 20 L plastic containers. The top of each trap was covered with 6 mm (internal width) galvanized steel mesh. The bottom of each ring was covered with plastic fly-screen material (1 mm internal width). The steel mesh was large enough to pass non-waterhardened eggs into the trap, but small enough to trap waterhardened eggs and exclude predators. A small amount of gravel was used as a ballast to prevent dislocation or overturning of the trap after deployment. On October 5, 1995 (prior to lake trout spawning), 20 egg traps were randomly placed throughout the area of each of the three spawning shoals. The traps were left out on the substrate surface of the shoals on October 31, 1995, at which time the trapped eggs were counted and their condition (viable, non-viable or opaque white, and fungus covered) assessed.

EMBRYO HATCHING SUCCESS BIOASSAYS

Egg incubators were constructed of 30.2 x 36.5 x 26.5 cm plastic milk crates, lined with galvanized steel mesh. A mesh size of 3.0-3.5 mm (internal width) was selected because a) the average waterhardened lake-trout egg has a diameter of 5-6 mm, and b) Balon and Noakes (1990) estimated the dorsal-ventral depth of a free lake-trout embryo (141 days , 4.4°C) as 3.25 mm. The incubators were designed to retain eggs and larvae, while maximizing water circulation and excluding predators. Thirty-five incubator sites were randomly selected on the three shoals throughout September 1995 (Appendix II). At each sampling site, substrate was removed and an incubator was placed into the excavated area. The removed substrate was then placed into the incubator (Figure 6).

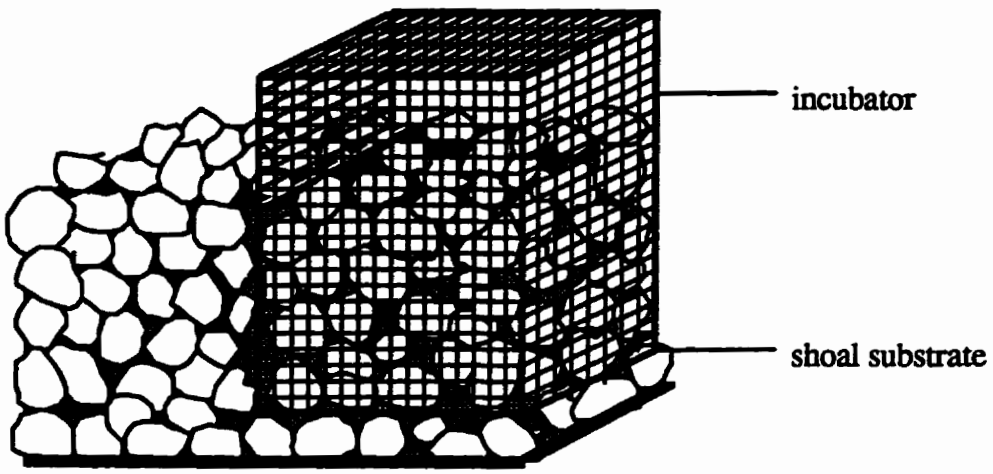

Figure 6. Incubator installation in shoal substrate of Lakes 20, 26, and 42. Diagram is not to scale.

Throughout the spawning season (October 7 - October 29, 1995) (between sundown and midnight), gill nets (3.8 - 5.0 cm mesh) were set for 15-minute intervals on and around the spawning shoals. Several female lake trout were stripped, and their eggs pooled and fertilized (in water) with milt from several males. The eggs were left overnight to waterharden in a 20 L pail, partially submerged in the lake to maintain a cool temperature. The next day, non-viable eggs (opaque white) were removed, and two hundred eggs were scattered over the substrate enclosed within each incubator.

Platts *et al.* (1983) distinguish two classes of fine sediment: large fine sediment (0.83 -4.71 mm), and small fine sediment ($\leq$ 0.83). The reason for the separation is that large fine particles can form a physical barrier to fry emergence, while small fine particles tend to decrease water permeability through spawning substrate (Platts *et al.* 1983).

To observe the effect of a single sedimentation event on embryo survival, hatching success was assessed on the Lake 20 shoal where 700 cm^3 of sand (diameter < 0.425 mm) had been added to the incubators, equivalent to a layer approximately 2.5 cm deep across the surface of the incubator. Incubators (up to a maximum of 3 if available) were placed in randomly selected sample sites. Approximately 75 % of the fine sediment was distributed across the surface of the substrate in the incubator, followed by the 200 eggs, followed by the remainder of the fine sediment. All of the incubators were covered with galvanized steel mesh secured with elastic cords. The incubators were retrieved May 21-24, 1996. Hatching success was assessed by counting the number of unhatched eggs.

MID-WINTER DISSOLVED OXYGEN

Interstitial water on Lake 20 was sampled using apparatus similar to that described by Gunn and Keller (1984). Known lengths of tygon tubing (5 mm internal diameter) were buried under one layer of substrate enclosed in five incubators. These incubators were not randomly chosen as they needed to be in close proximity to each other to facilitate easier winter access. On February 15, 1996, water was drawn through the tubing using a peristaltic pump. The water entered a plastic chamber which enclosed an oxygen meter probe. The water passed over the probe membrane and exited the chamber via a second tube (Figure 7). Once the water initially sitting the tubing was flushed out, readings were recorded for a subsequent 500 mL. The primitive design of the experimental setup had the oxygen probe's pressure compensating membrane outside of the sampling chamber. Therefore, it was necessary to pump the water very slowly to avoid increasing water pressure within the measurement chamber which causes erroneous dissolved oxygen readings. Ambient water oxygen concentrations were measured from water sampled at approximately 40 cm above the substrate. Samples for water chemistry were also collected, but were not analyzed due to laboratory service disruption arising from a public service strike.

NUTRIENT ENRICHMENT OF THE SHOAL ENVIRONMENT

The spawning shoal of Lake 20 is divided into a north and south section by a large rock outcrop (Figure 8). Six sampling sites were randomly selected in each of these sections. To test the response of periphyton to increased nutrient inputs, the north section of the shoal received inputs of both P and N in the form of P_2O_5- and N_2- containing

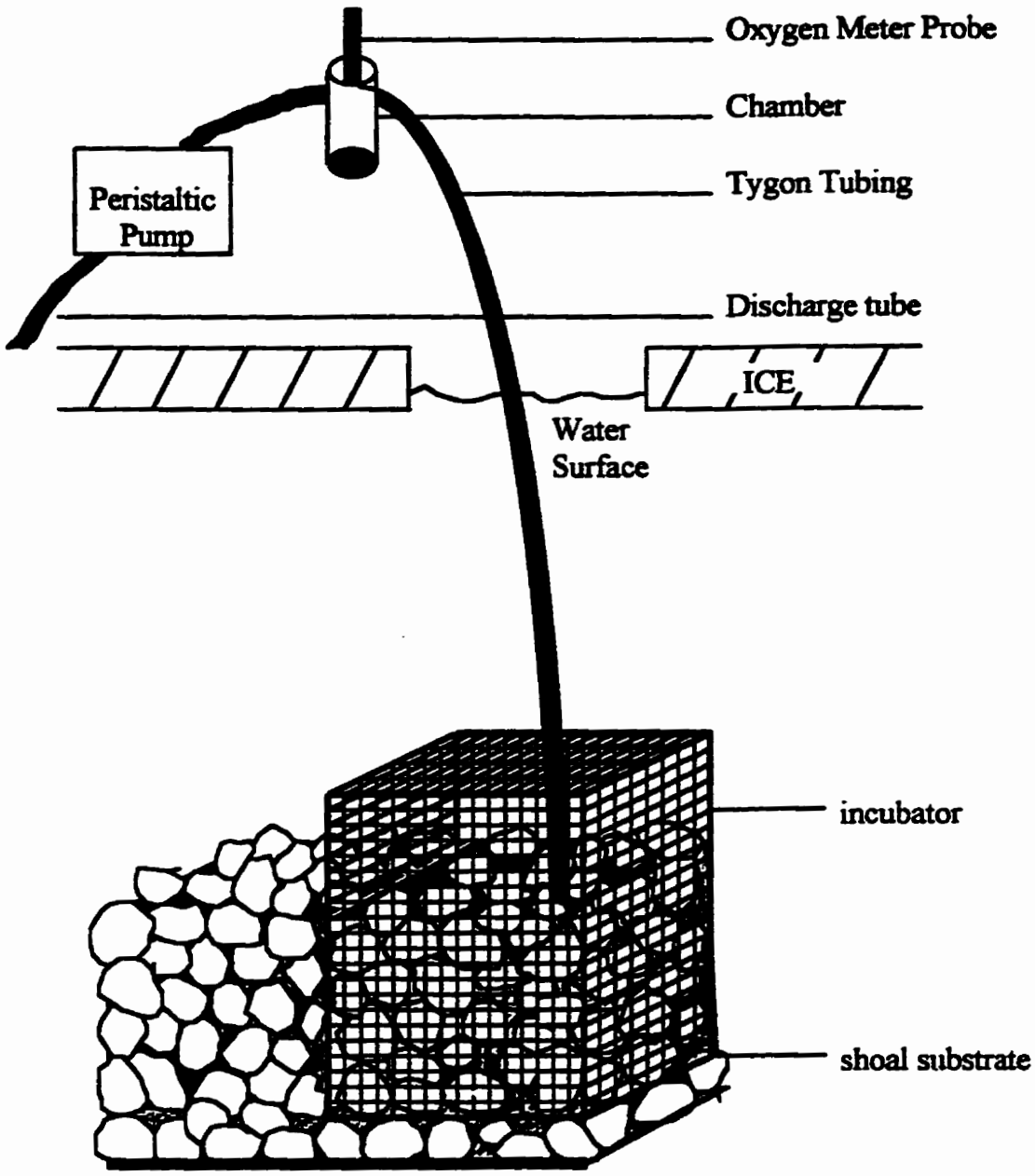

Figure 7. Sampling apparatus used to measure oxygen concentrations of water above and within the shoal substrate of Lake 20 during egg incubation. Diagram is not to scale.

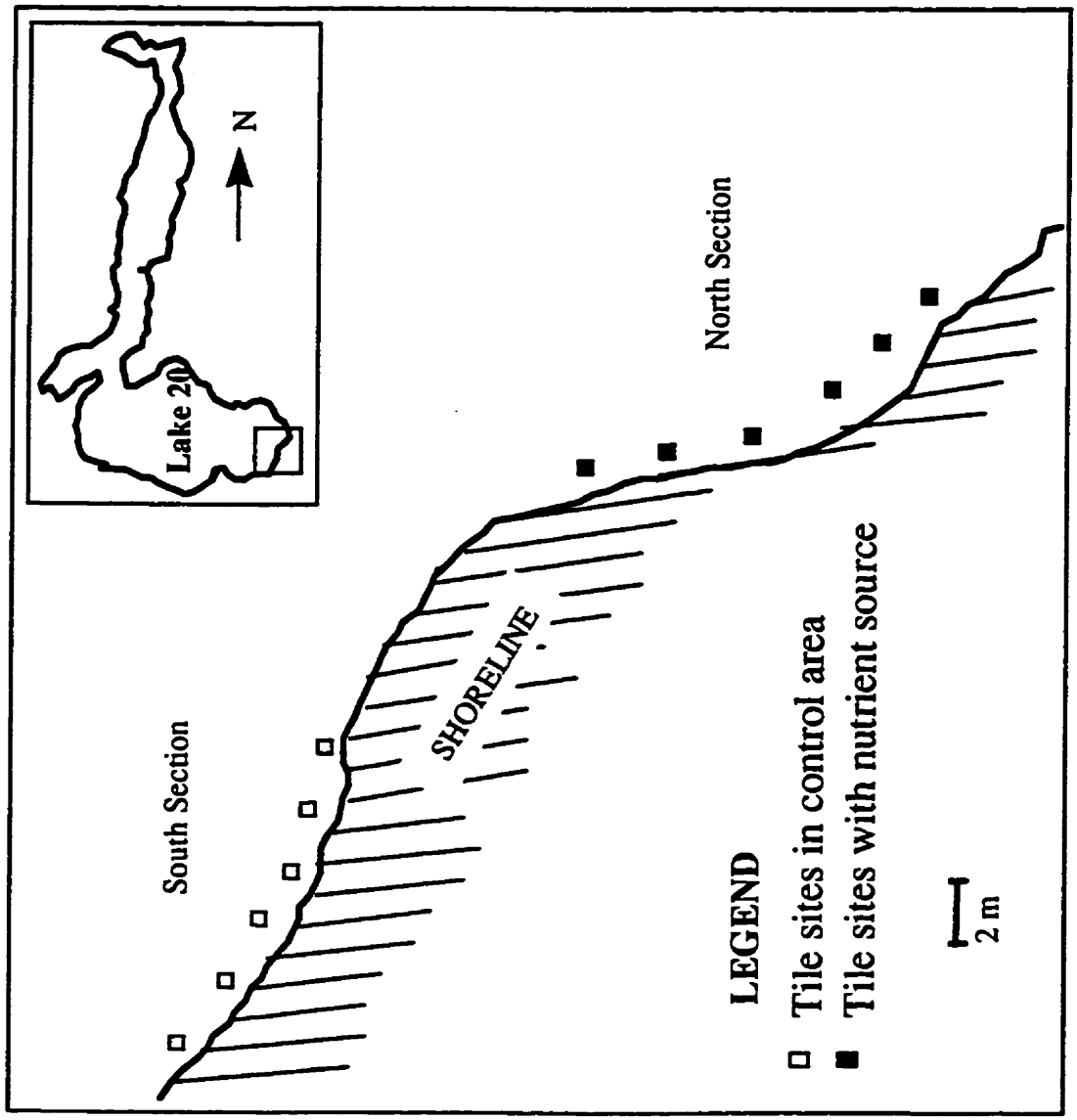

Figure 8. Location and design of the nutrient enrichment experiment on the spawning shoal of Lake 20.

fertilizers. Six plastic mesh cylinders (945 cm^3) were constructed and filled with fertilizer, and one cylinder was placed at each of the sampling sites in the north section (Figure 9). The cylinders were filled weekly (June 19 - July 25, 1996), with a total of 1042 g P and 4734 g N being released over the entire sampling period. The south section was used as a control area (Figure 8).

Granite-tile artificial substrates were chosen to measure the response of periphyton abundance to the point sources of N and P. These tiles were convenient and flexible regarding replication and sample location, and provided a standardized area (225 cm^2 upper surface area) to measure periphyton biomass.

On June 19, 1996, one tile was placed at each of the six sampling sites in both the north and south sections of the spawning shoal. On August 7, 1996 all of the tiles were carefully removed and placed in plastic bags for transport. To determine whether the nutrient sources were successful in raising the ambient N and P concentrations in the enriched areas, water samples were taken at each of three of the sample sites and at one and two meters from the sites parallel to the shoreline (Figure 9). This was repeated for the control area.

In the lab, the tiles were scraped and rinsed with distilled water, to remove all the accumulated periphyton from the surface. The material and water were put into plastic jars, sealed, and refrigerated (<-4°C) to allow suspended material to settle out. After two days the water above the settled material was drawn off with a pipette connected to a vacuum line. The remaining material was placed into preweighed aluminum dishes and oven-dried at 105°C until a constant dry weight was obtained. The dishes were ashed at

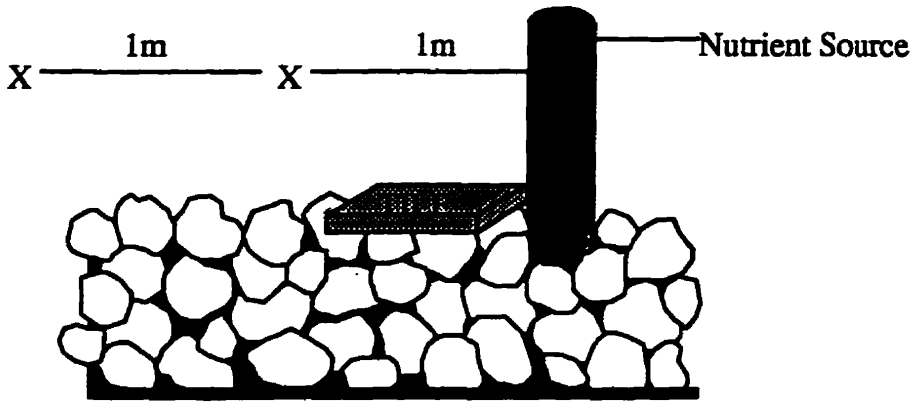

Figure 9. Spatial relationship of water sample sites for nutrient enrichment experiment on Lake 20. Nutrient sources in enriched area were placed adjacent to tiles. Water samples (X) were taken at 1 and 2 meters from the sample sites in both the control and enriched areas.

500°C for one hour and reweighed. For each sample the final ashed weight was subtracted from the dry weight to determine the weight of organic material.

STATISTICAL ANALYSES

Principal Components Analysis (PCA) (SPSS 1993) was used to explore how the seven habitat variables (depth, embeddedness, periphyton abundance, particulate debris abundance, percent vegetation, Fredle Index, and interstitial space depth) interacted with each other. The PCA maximizes the variance in the data which is explained by linear combinations of variables, in which successive components are constructed to be uncorrelated with previous ones. It often results in the summarization of the variance into only a few components, so that multidimensional data can be displayed effectively on a two- or three- dimensional graph that uses the PCA components as axes (James and McCulloch 1990).

Parametric statistics were used on data the exhibited both normal distribution and homogeneous variance. The hypothesis that substrate permeability was not significantly different between lakes was tested using ANOVA. Linear regression analysis was used to determine if there was a significant relationship between Fredle Index and substrate permeability.

Data made up of small sample sizes and/or non-normal data distributions violate the assumptions of the ANOVA. Therefore, non-parametric statistics were used to test for inter-lake differences in egg deposition, embryo condition, and hatching success data. Non-parametric statistics were also used to test for a significant effect of Fredle Index and

fine sediment on hatching success, and nutrient enrichment on periphyton abundance on the artificial tiles.

RESULTS

PHYSICAL ATTRIBUTES OF THE LAKE TROUT SPAWNING SHOALS

Lake 42

The spawning shoal on Lake 42 was approximately 156 m^2. This was the deepest of the three shoals and was composed of rounded smooth gravel and cobble substrate interspersed with large boulders (Figure 10). The substrate had relatively low Fredle Indexes and shallow interstitial spaces, with a moderate amount of periphyton and macrophyte growth, and little particulate debris on the shoal (Table 2, Figure 11). Although there was fine material located beneath the gravel and cobble, the surficial substrate was relatively unembedded by fine materials. Dead eggs and egg cases from the previous year were observed in ten sample plots during substrate sampling.

Lake 20

The spawning shoal on Lake 20 was approximately 100 m^2. The shoal was composed of smooth and very angular cobble and rubble (Figure 10). The substrate on this shoal had higher Fredle Indexes and deep interstitial spaces, relative to Lakes 42 and 26 (Table 2). The shoal sites exhibited no substrate embeddedness, no particulate debris or macrophytic growth, and low amounts of periphyton (Table 2; Figure 11). Dead eggs were observed in two sample plots.

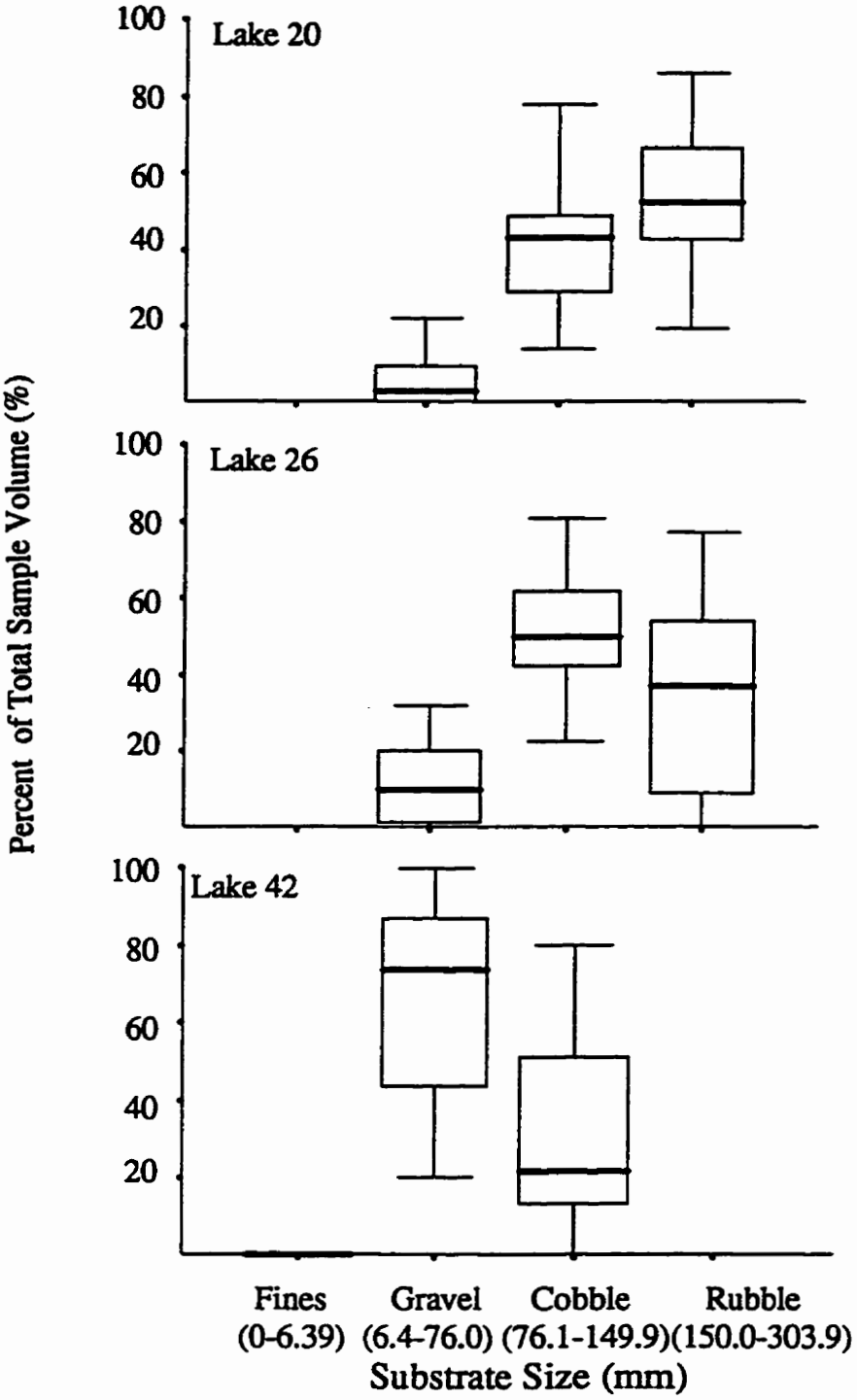

Figure 10. Boxplots displaying the percent of total sample volume by substrate class for the sampling sites on Lakes 20 (n=20), 26 (n=16), and 42 (n=20). The statistics conveyed by a boxplot are illustrated in Appendix VII.

Table 2. Mean ± S.D. of habitat variables on spawning shoals in Lakes 20 (n=20), 26 (n=16), and 42 (n=20).

Habitat Variable	Study Lake		
	20	26	42
Depth (m)	55 ± 17	41 ± 12	158 ± 8
Fredle Index	105 ± 34	87 ± 29	37 ± 12
Interstitial Space Depth (cm)	10 ± 6	6 ± 3	3 ± 1
Vegetation Cover (%)	0 ± 0	0 ± 0	4 ± 8
Particulate Debris Cover (%)	0 ± 0	1 ± 1	0 ± 0

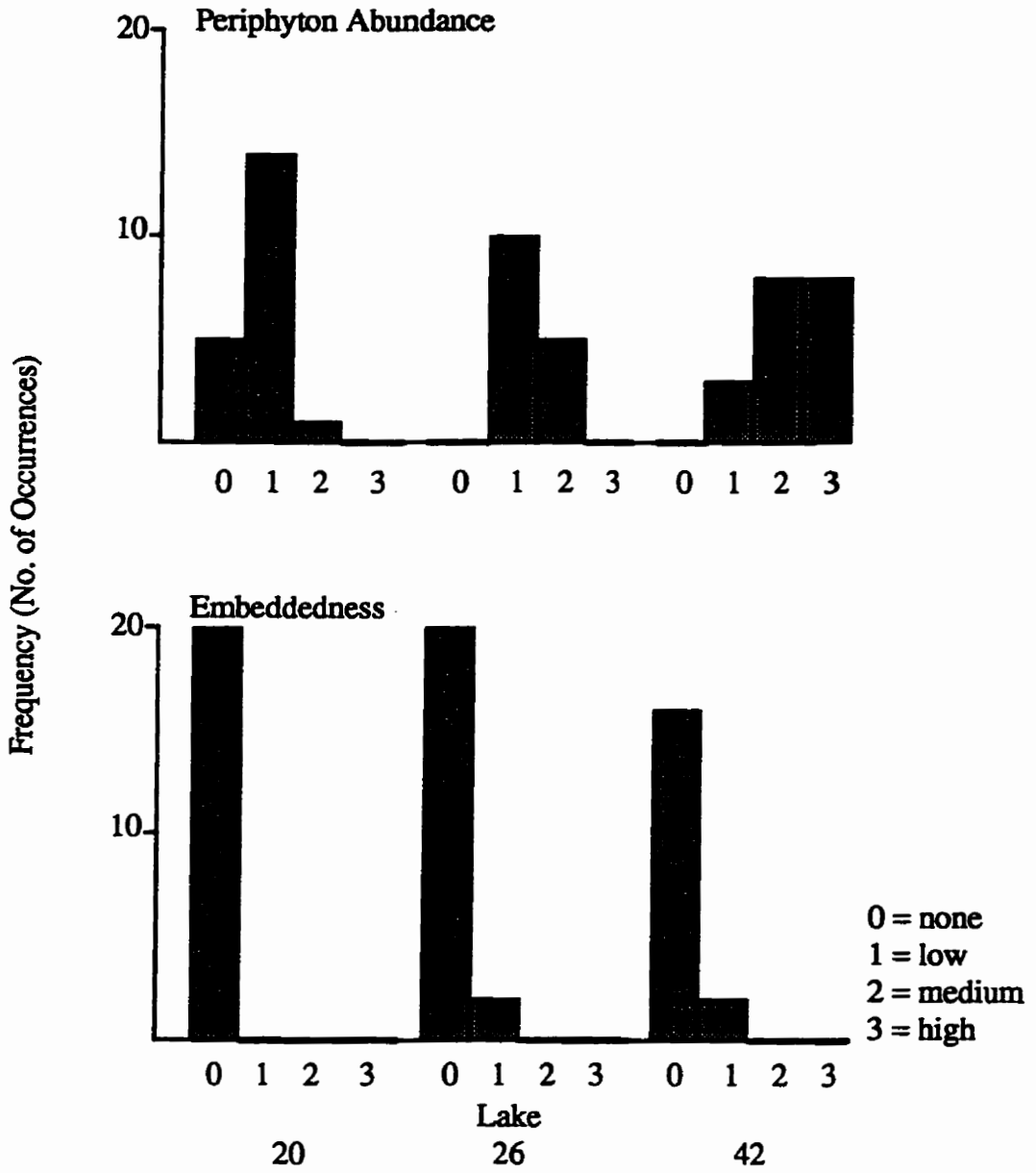

Figure 11. Histograms displaying the number of sites falling into each grading category for periphyton abundance and embeddedness.

Lake 26

Spawning shoal material in Lake 26 had been previously identified in various locations around the perimeter of the lake, but seemed to be concentrated in a 97 m^2 area located on the west shoreline. The shoal was comprised of round gravel, cobble and rubble interspersed with larger boulders (Figure 10). The Fredle Indexes and interstitial space depths of Lake 26 were generally higher than those of Lake 42 and smaller than those of Lake 20 (Table 2). The shoal had low embeddedness and little periphyton and particulate debris abundance. There were no macrophytes, and little periphyton (Table 2; Figure 11).

MULTIVARIATE ANALYSIS OF SPAWNING HABITAT

Each of the variables (Table 3) in the PCA appeared to be providing distinct information, and therefore all were considered as unique descriptors of the spawning shoals. The PCA reduced the seven dimensions of the fifty-six sites into two main variables (linear combinations of the original variables, or principal components). The first principal component (PC1), accounting for 45% of the variance, indicated a contrast between a) deeper sites with more vegetation, and periphyton on smaller sized substrate, and b) shallower sites with less periphyton on larger sized substrate. The second principal component (PC2), accounting for 20% of the variance, contrasted sites having a greater degree of particulate debris and embeddedness with cleaner non-embedded sites. A scatterplot of the fifty-six sites, using the two new linear combinations (PC1 and PC2), (Figure 12), shows that periphyton, particulate debris, and macrophyte abundance increased with increasing depth, while Fredle Index and interstitial space depth decreased

Table 3. Factor loadings[1] for the PCA on the physical features of fifty-six sites located on the spawning shoals within Lakes 20, 26, and 42.

Variable	PC1	PC2
Depth of Site	0.91	-0.28
Depth of Embeddedness	0.10	0.80
Fredle Index	-0.84	-0.11
Interstitial Space Depth	-0.75	-0.26
Particulate Debris Abundance	-0.46	0.75
Periphyton Abundance	0.77	0.17
Vegetation Abundance	0.50	0.20
% Variance	44.9	20.4

[1]Factor loadings represent of the correlation between the principal components and the original habitat variables.

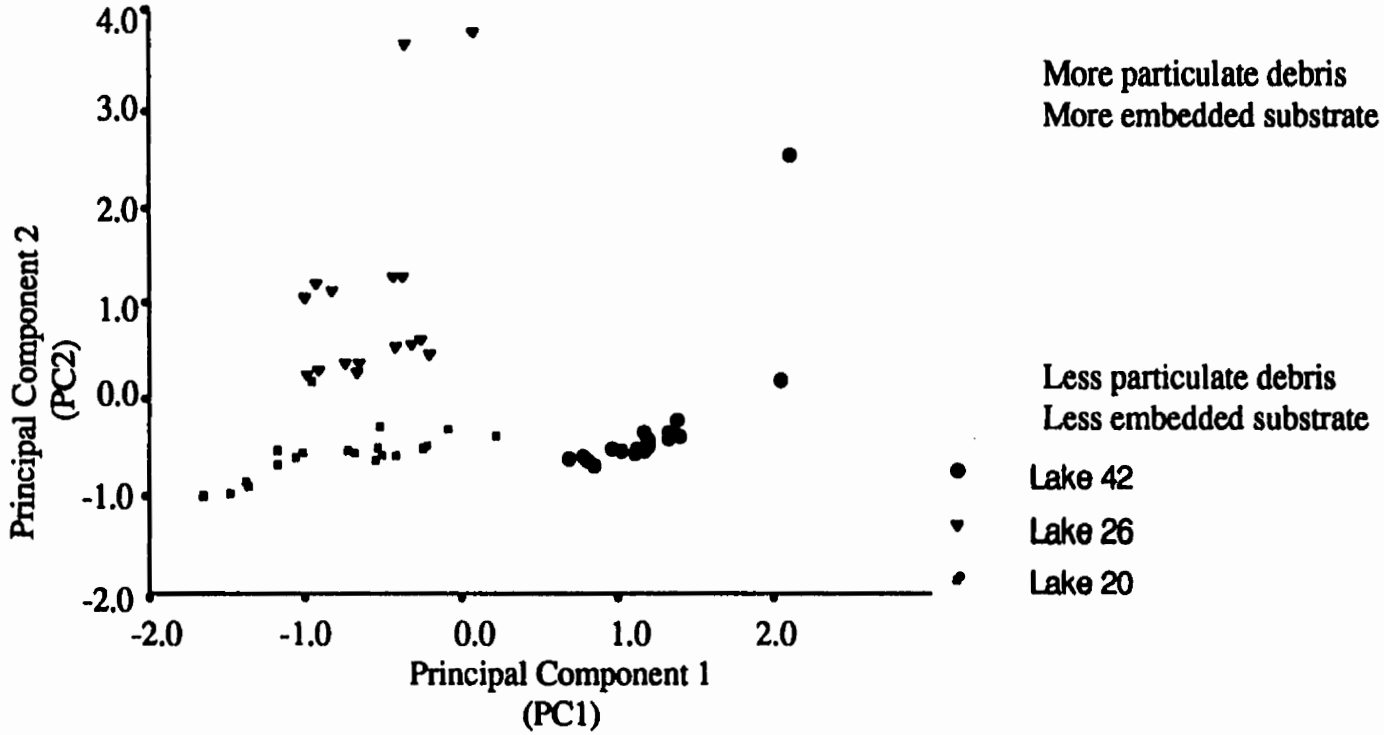

Figure 12. Principal Components Analysis- Ordination diagram of the fifty-six sample sites in relationship to the seven habitat variables measured on the spawning shoals within Lakes 20, 26, and 42.

with increasing depth. Figure 12 also shows that each shoal exhibits distinct combinations of physical features, causing the sample sites from each shoal to cluster together in PCA space

WATER FLOW MEASUREMENTS ABOVE AND WITHIN THE SHOAL

The water velocity above the shoal in Lake 42 was slightly greater than that of Lakes 20 and 26 (Figure 13). However, the water velocity within the substrate demonstrated little variation among lakes (Figure 13).

The diameter loss rate of the three replicate cylinders placed in the sites on the Lake 26 spawning shoal demonstrated homogeneous variance across a variety of Fredle Index classes, confirming that the cylinder measurements can be compared over a variety of substrate sizes (Figure 14). Lake 42 had a significantly less-permeable substrate than Lakes 20 and 26 (Tukey - HSD multiple contrast, $\rho<0.05$, Figure 15). Permeability (diameter loss above/ diameter loss below) data for Lakes 20, 26, and 42 were combined to determine the effect of Fredle Index on substrate permeability. Permeability had a significant positive linear relationship with Fredle Index, indicating that the interstitial water of larger substrate can more freely mix with ambient water compared to that of smaller substrate (Figure 16).

EGG DEPOSITION

Two hundred and seventeen eggs were trapped on the three shoals. The maximum number of eggs found in one trap was 55 in Lake 42. The mean ($\pm$ S.D) egg deposition density (n=20) was 77 ± 209 eggs m^{-2}, 61 ± 101 eggs m^{-2}, and 70 ± 123 eggs m^{-2} for

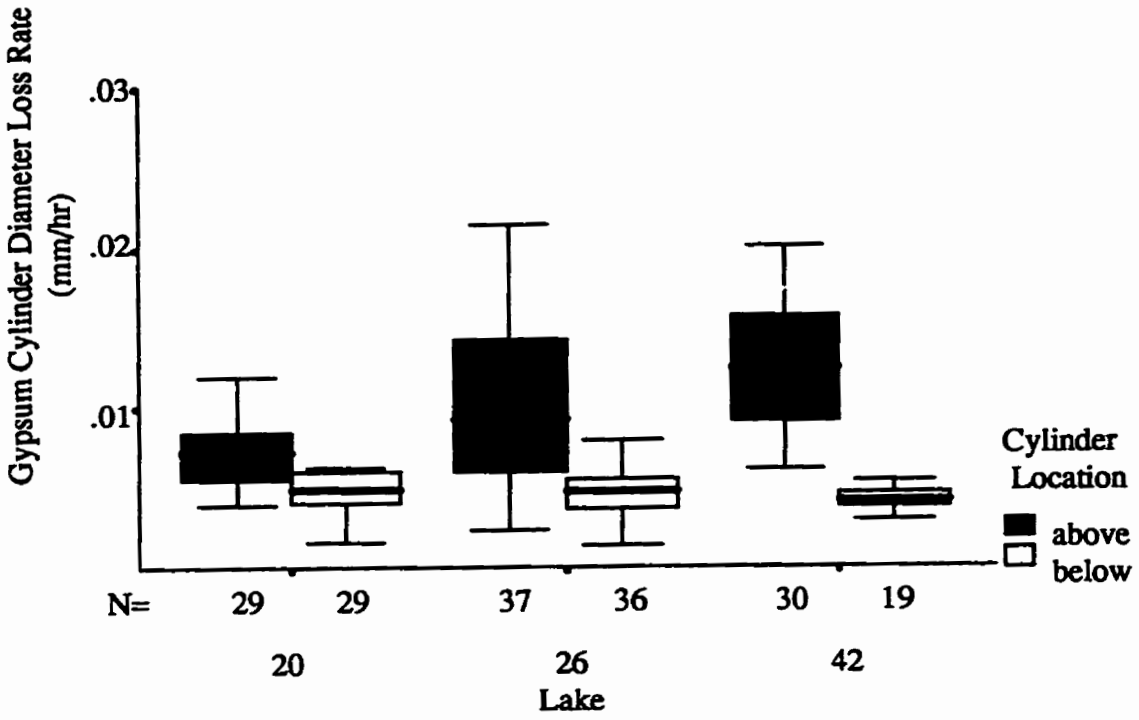

Figure 13. Box plots displaying diameter loss rates for gypsum cylinders suspended above and buried beneath the substrate on the shoals of Lakes 20, 26, and 42 (July 24 to September 7, 1995).

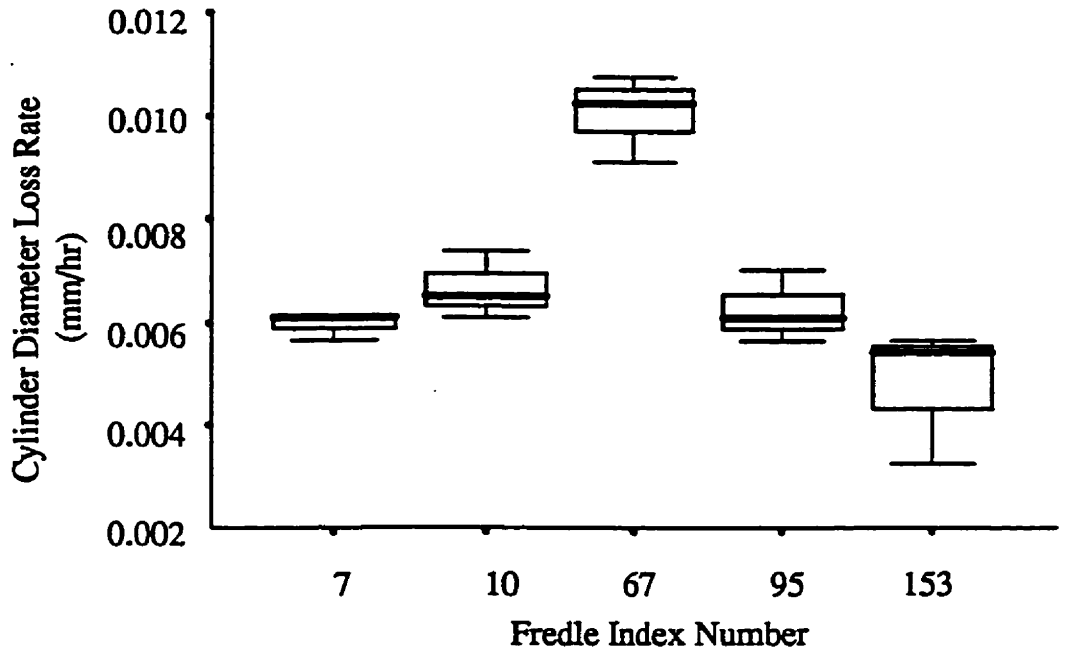

Figure 14. Box plots displaying the diameter loss rate for (n=3) cylinders placed in sites of varying Fredle Indexes on the Lake 26 shoal. The Levene test for homogeneity of variance shows that there is no significant difference in the variance of the diameter loss rate for the different Fredle Index numbers ($p = 0.112$). This indicates that the turbulence measured by the cylinders in various substrate sizes exhibit homogenous variance and can be can be compared for differences.

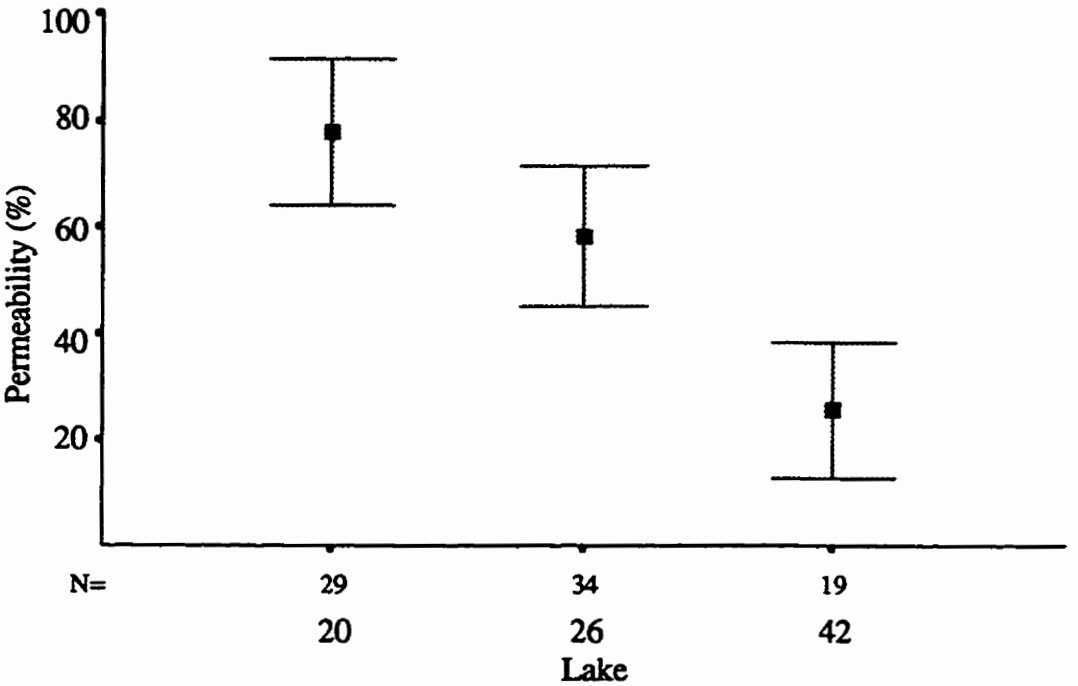

Figure 15. Mean± S.E. of permeability (diameter loss above / diameter loss below) measurements of the substrate on the shoals in Lakes 20, 26, and 42. The permeability of Lake 42 substrate is significantly lower than the substrate on Lakes 20 and 26 (p <0.05).

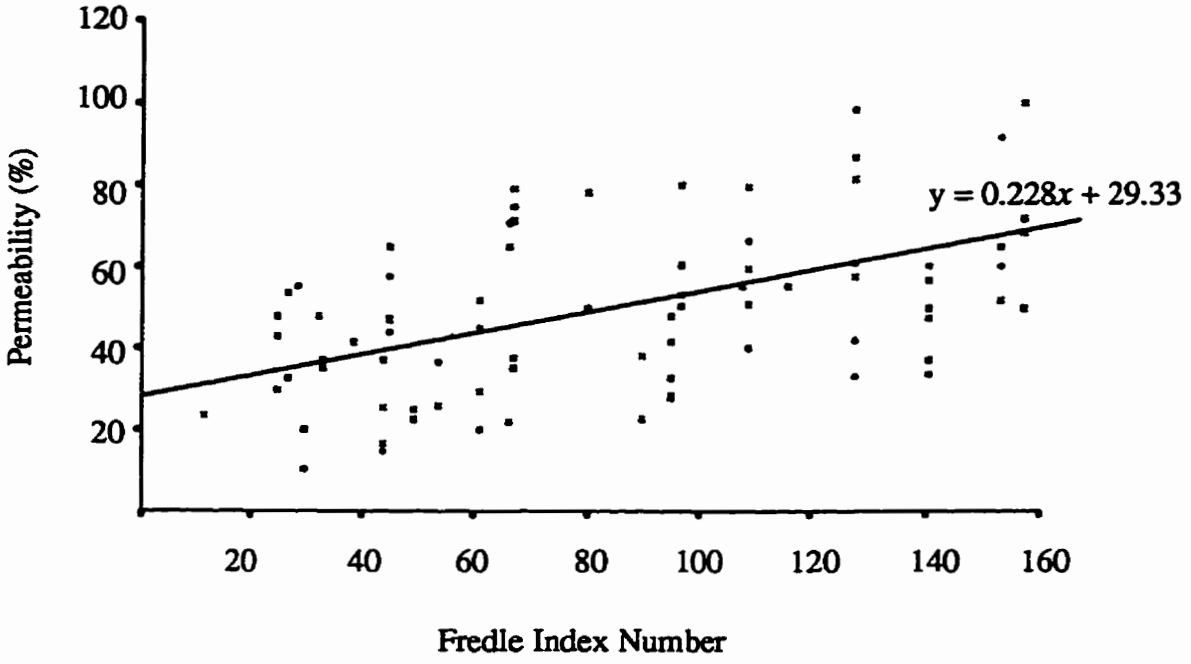

Figure 16. Relationship between substrate permeability and Fredle Index numbers for substrate of the shoals in Lakes 20, 26, and 42. The linear relationship is significant (r^2=0.24, p=0.000, n=82).

Lakes 42, 20, and 26 respectively. Forty five percent of all the eggs trapped in the three lakes appeared to be viable, and 32% appeared non-viable or opaque white in appearance. Nine percent of eggs appeared to be covered with fungus (Table 4). There were no significant differences in the total number of viable eggs (K-W, ρ=0.8706), non viable eggs (K-W, ρ=0.8392), or egg density among the three lakes (K-W, ρ=0.7353). There were significant differences among the lakes in the number of fungus covered eggs trapped (K-W, ρ=0.0158), with Lake 20 having the highest number of fungus covered eggs.

EMBRYO HATCHING SUCCESS BIOASSAYS

When the incubators were retrieved it was apparent that the mesh covering the incubators had not prevented free-swimming embryos from escaping. Therefore hatching success was estimated as 200 minus the number of remaining eggs in each incubator. After determining that there were no significant differences in hatching success between Lakes within Fredle Indexes classes 1, 2, 3, and 4 (K-W, $p<0.05$), I combined the hatching success data from the three lakes. Hatching success was not the same for all four Fredle Index classes (K-W, ρ=0.0487). Mann-Whitney U tests on two Fredle Index classes at a time were used as *post hoc* multiple contrast tests and confirmed that Fredle Index Class 3 had a significantly higher hatching success (75%) than Fredle Index Classes 1 (44%), 2 (45%), and 4 (35%), (M-W U, $\rho<0.1$, Figure 17). The fine sediment which was added to incubators in the fall was absent upon spring incubator assessment. There was no significant effect of added fine sediment on embryo hatching success (t-test, ρ=0.305, n=21, Figure 18).

Table 4. Number of total viable, non-viable, and fungus covered eggs trapped on the shoals of Lakes 20 (n=20), 26 (n=20), and 42 (n=20). Mean egg density ± S.D. is calculated using all the eggs trapped on each shoal.

	Study Lake			
Egg status	20	26	42	Lakes combined
Viable	19	45	51	115
Non-viable	26	19	35	80
Fungus covered	21	1	0	22
Total eggs trapped	66	65	86	217
Density eggs m^{-2}	61 ± 101	70 ± 123	77 ± 209	69 ± 146

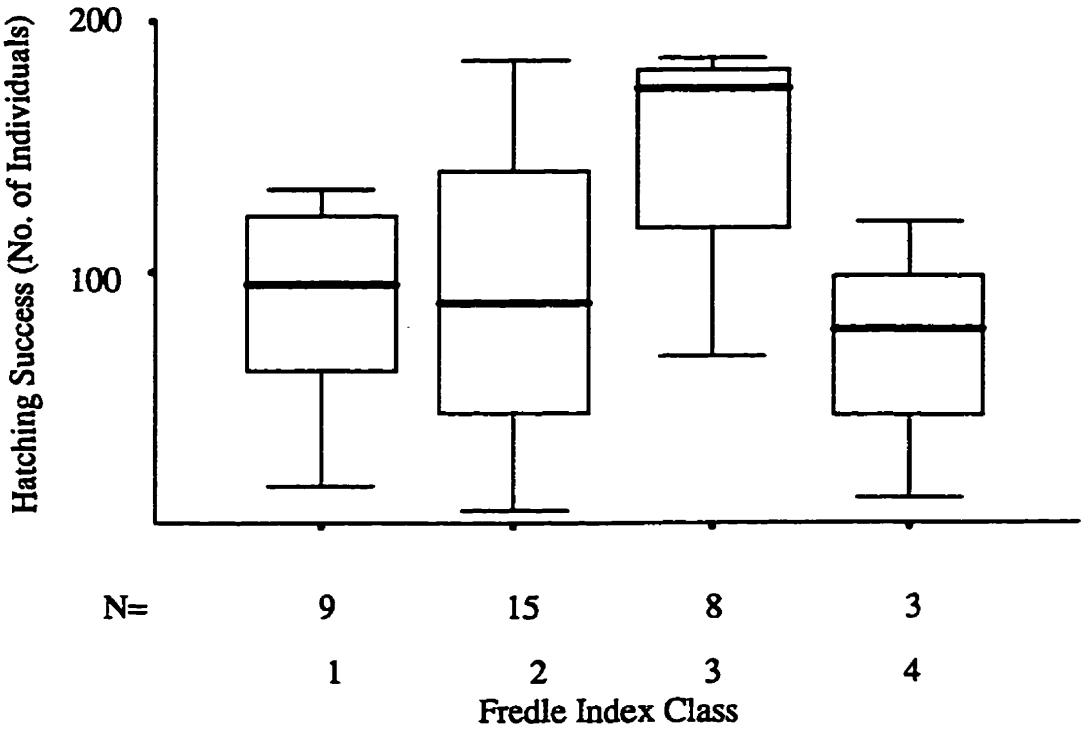

Figure 17. Box plots displaying the hatching success for Fredle Index classes 1, 2, 3, and 4 for Lakes 20, 26, and 42 combined.

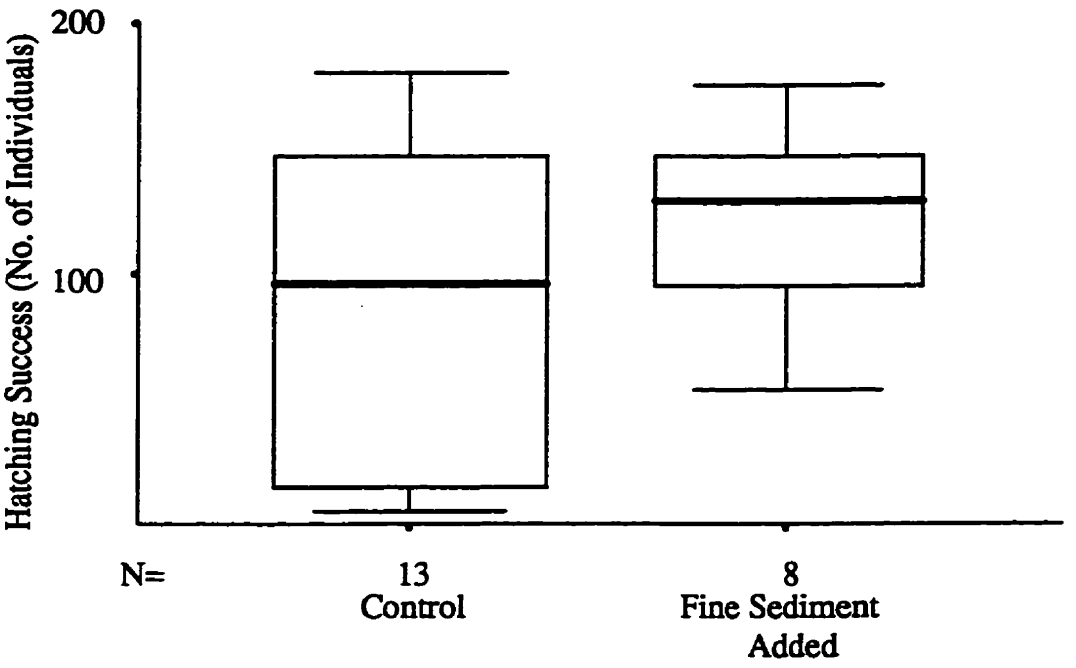

Figure 18. Box plots displaying the hatching success of the incubators with no added fines sediment (control) and added fine sediment. The two groups are not significantly different (t-test, p=0.305).

MID-WINTER DISSOLVED OXYGEN

On February 15, 1196 the temperature and oxygen concentration of the water below the ice surface were 1.5°C and 9.7 mg L^{-1} respectively. The oxygen concentration for incubator sites with Fredle Index numbers of 45, 99, 141, 155, and 193 were 9.0, 9.1, 8.9, 9.5, and 9.5 and mg L^{-1} respectively. Although further sampling is required to confirm any significant relationship, there does appear to be an higher O_2 concentration in the substrates with larger Fredle Index numbers.

NUTRIENT ENRICHMENT OF SHOAL ENVIRONMENT

Concentrations of both P and N were significantly different in the control and enriched areas at 0, 1, and 2 m away from the sampling site (M-W U, $\rho<0.05$, Table 5), indicating that the nutrient sources were successful in increasing the ambient P and N concentrations. Tiles from the Lake 20 control (n=3) and nutrient enriched area (n=6) had a mean organic mass 0.02g and 0.05 g respectively. There was a significant effect of nutrient concentration on the abundance of organic material on the tiles (M-W U, ρ =0.0201).

Table 5. The *p* values of a pariwise comparison using the Mann-Whitney U test as a multiple contrast of mean embryo hatching success between substrates different Fredle Index classes. A Bonferroni correction factor[1], was used to determine significance (n=35).

Fredle Index Class	1	2	3	4
1	—	—	—	—
2	0.9762	—	—	—
3	0.0161	0.0201	—	—
4	0.5175	0.5940	0.0662	—

[1] Bonferroni Correction Factor

The *p* values presented in the above table are those resulting from individuals pairwise comparisons using the Mann-Whitney U test. For all comparisons to be valid as a group, the alpha level chosen must be divided by the number of comparisons made, in this case six. Therefore, if an alpha level of 0.05 was chosen, any significant *p* values would have to be less than 0.008.

DISCUSSION

SPAWNING SHOAL CHARACTERISTICS

Substrate Size and Composition

The substrate analyses for Lakes 20, 26, and 42 were in general agreement with other studies of inland lake-trout reproductive habitat. Spawning substrate on the three shoals ranged from gravel (0-6 mm), to small boulders (150-303 mm), at depths between 0.2 and 1.6 m. Similar spawning shoal material has been described as clean rubble, 20-200 mm in diameter, located in water depths between 0.1-5.0 m (Martin and Olver 1980; Evans *et al.* 1991). Lake-trout surveys report that spawning takes place mostly on cobble (64-256 mm) and boulders (>256 mm) (Hansen *et al.* 1995). The interstitial space depths on the three shoals ranged from 10 to 40 cm, which are consistent with interstices (>10 and < 50 cm) measured of substrates in 1- 4 meters of water (Kelso *et al.* 1995).

Trends exhibited by Substrate Size, Periphyton, Macrophytes and Particulate Debris

The Lake 42 spawning shoal was deeper, with smaller substrate and a greater amount of periphyton and vegetation than the Lake 20 and 26 shoals which were shallower, cleaner sites with relatively larger substrate. Higher organic material abundance may be explained by the higher nutrient values of Lake 42 compared to those of Lake 20. However, wind-caused currents and waves are known to play a key role in

keeping the shoal areas swept clean of silt and particulate debris (Sly 1984; Nester and Poe 1987; Gunn 1995).

The PCA illustrated an increasing abundance of periphyton, macrophyte vegetation, particulate debris and smaller substrate with depth. Sedimentation of small nutrient-rich particles, as a result of periodic wave actions, usually increases with increasing water depth and wind fetch (Hakanson 1977; Hannson 1992). Periodic wave energy usually occurs in the form of orbital circulation of water particles, and peripheral wave action (waves breaking on the shore) (Hilton 1985), with both actions dissipating with depth. Orbital water movements often extend to the sediments, causing the disturbance and erosion of the sediment bed (Lick 1982). Peripheral wave action is the dominant mode of resuspension of sediment which is subsequently deposited in the central portions of the lake (Larsen and MacDonald 1993).

Macrophyte and periphyton growth may be enhanced by the nutrients associated with the fine sediments, which tend to accumulate in deeper lower energy environments. There is also a negative relationship between periphyton and vegetation abundance, and the increasing mechanical force of wind-induced water motion (which increases the probability of biomass removal, seeding displacement and propagule displacement) (Keddy 1983; Chambers 1987).

There is a dearth of research on the relationship between shoreline vegetation and the wind energy acting on a lake basin. However, the basic effect of trees in agricultural wind breaks is to reduce windspeed on the downside of the barrier (Frank and Willis 1972; Sturrock 1972; Tomari *et al.* 1980; DOC 1984;). Therefore, shoreline deforestation may alter the local patterns of wave approach or current flow which are

responsible for the accumulation of fine particulate and organic material in the area (Evans *et al.* 1991).

The physical and bathymetric characteristics of individual spawning shoals may result in site-specific responses to terrestrial disturbances associated with timber harvesting. These varying responses may be beneficial or deleterious to lake trout embryo survival and reproductive success (Evans *et al.* 1991). Therefore, as recommended for the Great Lakes (Marsden *et al.* 1995a), site specific measurements of wave energy and hydrodynamic patterns should be included in lake trout reproductive habitat and embryo survival studies.

EGG DEPOSITION

Egg deposition densities for Lakes 20, 26, and 42 (69 ± 146 (S.D.) eggs m^{-2}) were similar to the 0-370 eggs m^{-2} measured in waters less than 4.5m deep in the Great Lakes (Kelso *et al.* 1995). Egg densities have been measured up to 1500 eggs m^{-2} in Ontario inland lakes (Martin and Olver 1980). Recently, in Whitepine Lake, Sudbury, Ontario, egg densities were recorded as high as 1224 and 3136 eggs m^{-2} (McAughey and Gunn 1995).

EMBRYO HATCHING SUCCESS BIOASSAYS

Survival of lake trout embryos average 14-59 % in cobble and rubble substrate (Casselman 1995; Eshenroder *et al.*1995; Marsden *et al.* 1995b). I observed increased hatching success (75%) in the substrates in Fredle Index class 3 (40 % cobble and 60% rubble) compared to classes 1 and 2 (44%, 45%), which is consistent with the positive

relationship determined between Fredle Index and emergence of salmonid embryos from natural gravel mixtures (Lotspeich and Everest 1981; Chapman 1988). Embryos incubating in substrate with larger Fredle Indexes, and higher permeability, are most likely benefiting from increased oxygen delivery to, and waste removal from the incubating habitat.

Decreased hatching success (35%) in Fredle Index class 4 (20% cobble and 80% rubble) substrate, may be due to physical shock or suffocation. Physical shock or trauma during time of early embryonic development (*i.e.* epiboly, germ ring closure) can cause mortality of lake trout embryos (Casselman 1995; Manny *et al.* 1995; Perkins and Krueger 1995). All of the incubators with substrate in Fredle Index class 4 were located on the shoreline shoals of Lakes 20 and 26. The relatively higher water flow through larger substrates, in addition to peripheral wind and wave energy (prior to ice cover), may have shocked eggs sufficiently to increase embryo mortality. Too much wave action can also damage eggs by scouring them with suspended sediments, or by dislodging them from the substrate (Marsden *et al.* 1995a). In the Great Lakes, eggs incubating in deeper water were found to be less vulnerable to wave-induced damage or displacement than those in the shallows (Marsden *et al.* 1995b). Any effect of physical trauma in this study may have been exaggerated because the eggs were scattered over the substrate after they had waterhardened. This would prevent them from swelling and entrapping themselves more securely in the interstices, thus leaving them more vulnerable to disturbance and displacement.

Decreased hatching success observations in Fredle Index class 4 substrate may also could also be an effect of increased embryo suffocation mortality (Soderberg and Krise

1986). Although the interstitial depth increases with Fredle Index, the number of available interstices declines with larger substrate (Marsden *et al.* 1995a). This may result in "egg crowding" and impaired water circulation.

INCUBATION ASSESSMENT

The incubators used for the hatching bioassay were designed to expose the embryos to a natural incubating environment. However, free-swimming embryos could escape through the mesh once their yolk sac was absorbed and no longer restricting their exit. My inability to account for all 200 embryos upon incubator retrieval introduced the potential to overestimate hatching success.

Disappearance of eggs from incubators where the escape of free swimming embryos was not possible, has been observed in both field and laboratory studies (Casselman 1995; Perkins and Krueger 1995; Manny *et al.* 1995; Marsden *et al.* 1995b). Marsden *et al.* (1995b) documented that no eggs disappeared from the incubators held in laboratory conditions, and thus attributed the disappearance of *'in situ'* eggs to invertebrate predation. In contrast Manny *et al.* (1995) and Casselman (1995) documented egg disappearance from laboratory incubators. Upon microscopic examination of the incubator cells, Casselman (1995) concluded that the incubator cells contained highly decomposed early-hatched fry.

Although further investigation is required to address this phenomenon of embryo disappearance, it is likely that my hatching success results (intended to be a measure of embryo survival) included prematurely hatched eggs which were then lost to predation or decomposition. Nevertheless, this exaggeration should have been consistent throughout

the incubation trials within each lake for two reasons. First, premature development and hatching is stimulated by early accumulation of thermal units (early fertilization at relatively high temperatures) (Casselman 1995). Since incubators within each lake were supplied with embryos from the same source, at the same time, they should all have been exposed to the same temperature regime. Secondly, uniform screen size subjects incubator, and its contents, equally to invertebrate predation. In addition, retrieval of incubators with numerous unhatched eggs, and a visible abundance of invertebrate fauna, suggest that hatched embryos, if any, may be more vulnerable to invertebrate predation. Despite the shortcomings of these incubators for quantifying stages of embryo development and survival, these devices provided a relatively natural incubating environment, and were useful for comparison of relative survival among sites.

EFFECTS OF TIMBER HARVESTING PRACTICES ON LAKE TROUT REPRODUCTIVE HABITAT

The insignificant effect of fine sediment on embryo hatching success in Lake 20 was not consistent with previous studies (Phillips 1971; OMNR 1984), which indicated a positive relationship between increased fine material and embryo mortality. Almost none of the fine sediment that had been added was present when the incubators were recovered. The incubator screen would permit movement of fine material to deeper layers of substrate which, accompanied with any disturbance and removal of the fine sediment by fall wind and wave energy, may diminish the effect of fine sediment on hatching success.

Well established relationships exist between nutrient regimes and primary productivity (Dillon and Rigler 1974; O'Brien and DeNoyelles 1978; and Canfield and Bachmann 1981; Likens *et al.* 1972). The addition of N and P fertilizer to the experimental area stimulated growth (2.5 times that of the control area), which suggests that periphyton abundance and accumulation is limited by P and/or N availability. The N:P ratio in the enriched area was approximately 5:1. As a rule, an N:P ration lower than 15 indicates nitrogen limitation (Levine and Schindler 1992). Although the results suggest that nutrient enrichment does increase periphyton abundance, comparatively, both the pre- and post-harvesting nitrate stream concentrations in the Hubbard Brook Forest were much higher (0-1 mg/L and 20-80 mg/L respectively).

One of the biggest differences between shoals in Lakes 20 and 42 is the abundance of fine sediment and periphyton. Therefore, embryos on sites with equal Fredle Index classes would be expected to have a decreased survival rate in Lake 42. However, embryos in substrates of similar composition throughout all three lakes demonstrated no significant survival differences. It is possible that the degree of fine material and organic material was not high enough to have a significant negative impact on embryo survival or hatching success. However, it is likely that substrate disturbance during a) substrate analysis, and b) incubator installation, was sufficient to remove the biomass and fine material from the incubating habitat, thus minimizing the effect of fine materials on hatching success.

Investigating the effects of siltation and nutrient enrichment has played an essential role in understanding the threats of unnatural disturbance to lakes, spawning

shoals, and incubating embryos. However, studies of lake-trout reproductive habitat are limited for two reasons. First, many studies have investigated the response of survival to only one variable (*e.g.* siltation). Secondly, much of our understanding of lake-trout habitat degradation results from the extrapolation of findings from studies of long-term shoreline disturbance (*e.g.* urbanization and development), instead of the specific activities associated with timber harvesting. It is critical to treat the unique issues of timber harvesting, and the dynamics of this habitat, on a much broader scale.

This study has provided a characterization of the physical features of the preferred lake trout reproductive habitat in three small undisturbed northwestern Ontario lakes. The hydraulic measurements indicated that substrate permeability increases with substrate size which may have a direct effect on lake trout embryo hatching success. The fine sediment which was added to incubators in the fall was absent upon spring incubator assessment. At the single fine sediment dosage tested in this study (equivalent to a layer approximately 2.5 cm deep across the surface of each incubator), lake trout hatching success was not significantly affected. Nutrient enrichment of a shoal area indicated that periphyton abundance increased with nutrient addition (N and P) and is most likely nitrogen limited, although the effects of this, on reproductive habitat, are not presently known.

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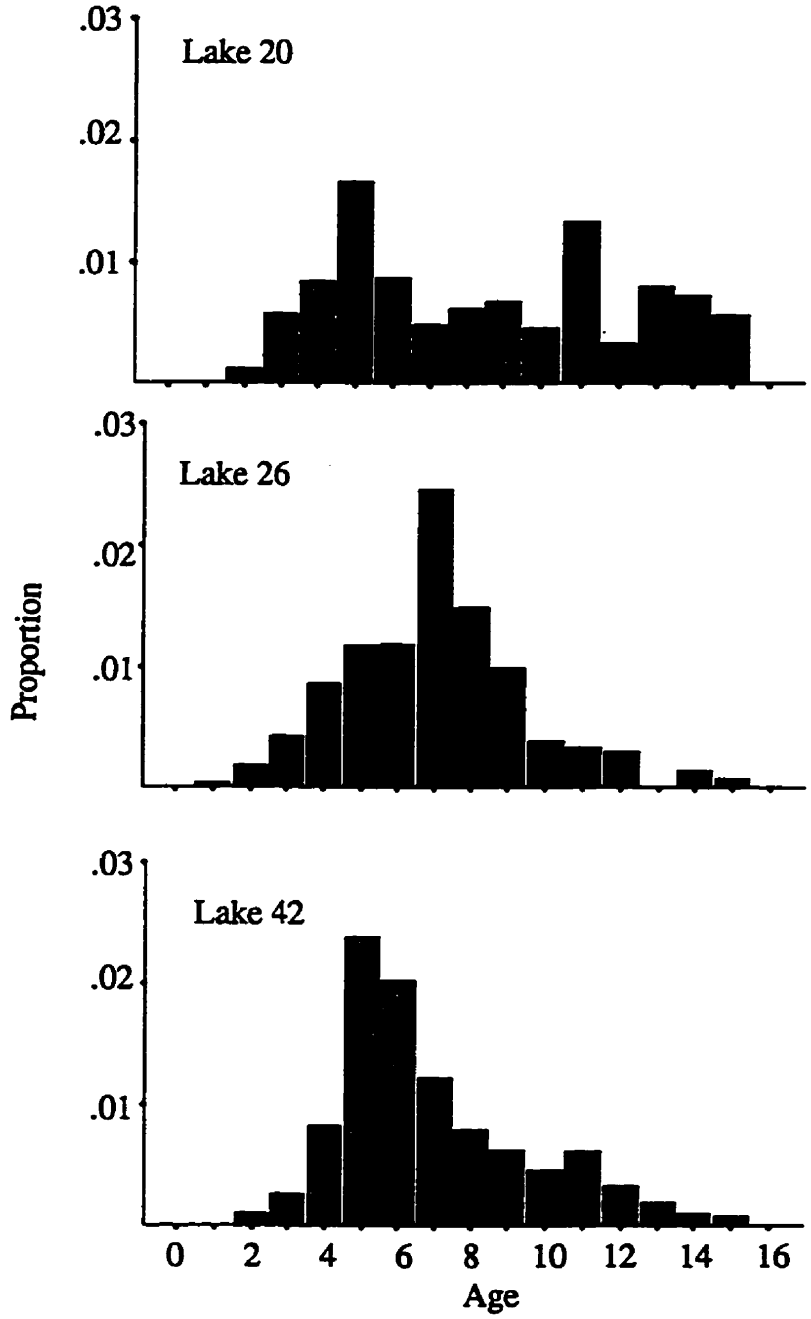
APPENDIX I

Lake trout age distribution in Lakes 20 (1992,1993), 26 (1992, 1995), and 42 (1992-1994) as reflected by fall netting (OMNR unpublished data).

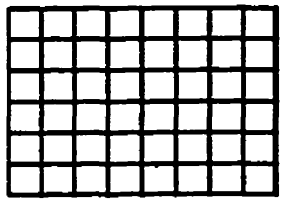


APPENDIX II

RANDOM SELECTION OF:

Spawning shoal sample plots, egg traps locations, and nutrient enrichment sites

Each shoal was divided into 1 x 1 m squares, similar to the following grid. Each intersection point, representing a potential sample plot center or egg trap location, received a number. All the numbers were put on individual pieces of paper. Twenty numbers, were drawn and the corresponding points, located on the shoal using markers and ropes, were sampled. This process was repeated to determine the egg trap locations. This process was also used to establish the sample sites for the nutrient enrichment experiment.



← Grid used for random selection

Interstitial spaces

A circular plastic grid (42 cm in diameter) was used to select interstitial spaces for sampling. Each square was numbered and represented a $4cm^2$ area. For each plot 10 numbers were drawn. The grid was laid over the plot and the interstitial space in the plot's corresponding 10 points were sampled. If there were more than one interstitial space in the area, the one closest to the center was measured. If there was no interstitial space, another number was selected.

Gypsum cylinder deployment and incubator sites

Sample plot numbers were drawn until, separately, a) at least five sites were selected for each shoal for substrate permeability measurements, b) five sites were selected for cylinder sampling variance measurements on the Lake 20 shoal, c) 35 incubator sites were drawn from all three shoals combined, and d) an additional 9 incubator sites were selected from the Lake 20 to receive added fines.

APPENDIX III

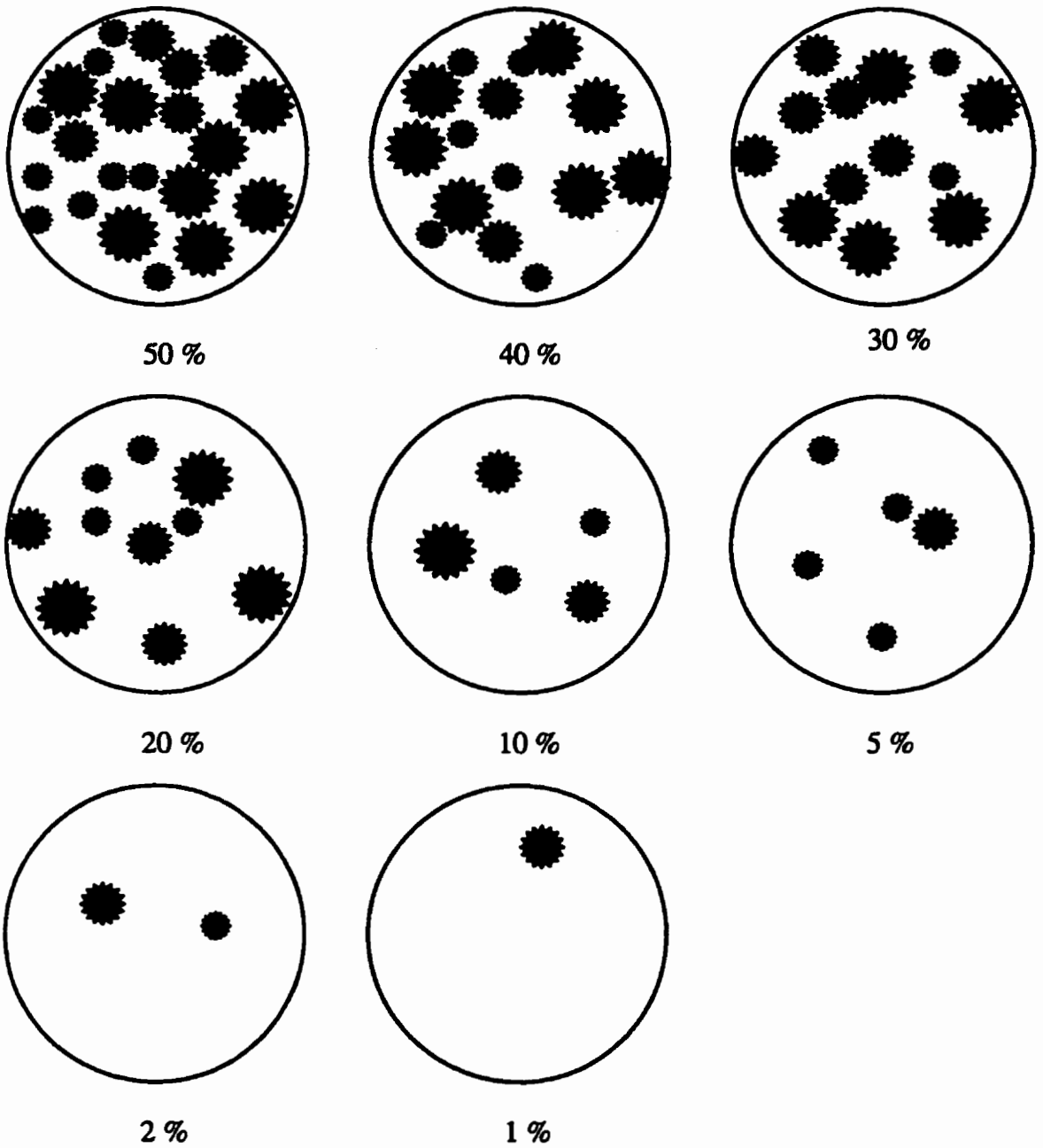
PERIPHYTON ABUNDANCE

The criteria for determining the relative abundance of periphyton is presented in the following table.

Relative abundance	Grading	Criteria
none	0	-no visible periphyton
low	1	-> 50 % substrate surface visible -sparse periphyton abundance
medium	2	-50% substrate surface visible -periphyton easy to remove by creating moderate current with hand movement
high	3	-< 50 % substrate surface visible -periphyton difficult to remove by creating moderate current with hand movement

APPENDIX IV

Percent cover charts used to visually estimate vegetation and particulate debris abundance in sample plots. Revised from Ontario Institute of Pedology (1985).



APPENDIX V

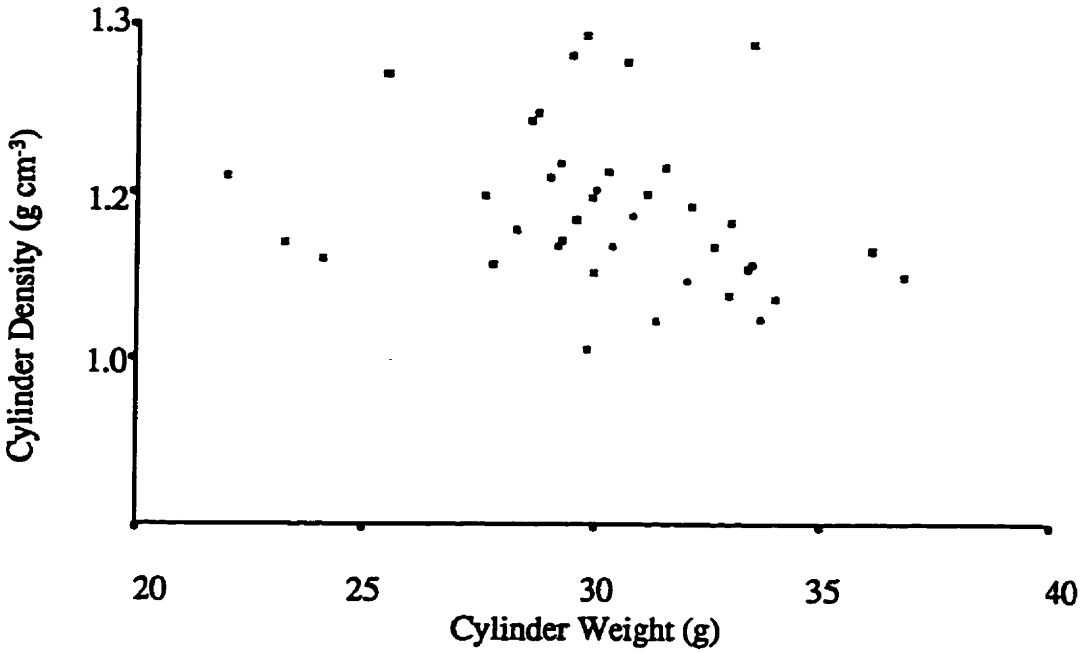
RELATIVE EMBEDDEDNESS

The criteria for determining the relative embeddedness are presented in the following table.

Relative embeddedness	Grading	Criteria
none	0	-no visible surficial fines in gravel, cobble, rubble or boulder material -minimum of 2 layers clean surface
low	1	-no visible surficial fines in gravel, cobble, rubble or boulder material -only 1 layer clean surface
medium	2	-fines visible in larger surficial substrate -greater than 50 % of substrate diameter exposed
high	3	-fines visible in larger substrate -less than 50 % of substrate diameter exposed

APPENDIX VI

Relationship between cylinder density and weight. The linear relationship is not significant ($r^2 = 0.09$, $p = 0.0557$, n = 40).



APPENDIX VII

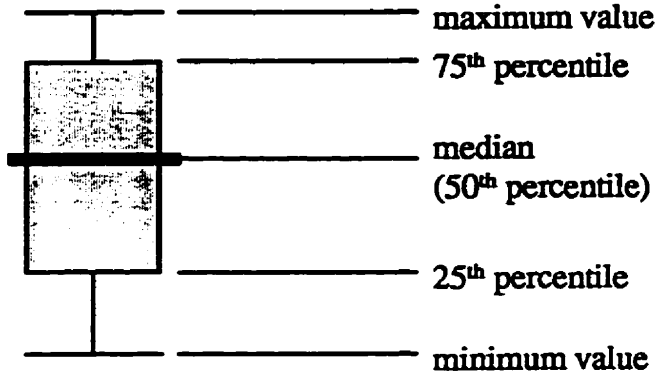
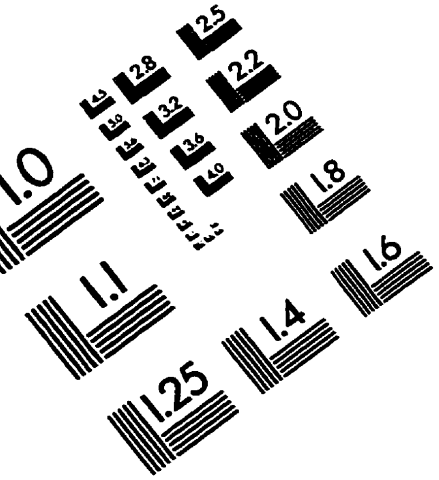
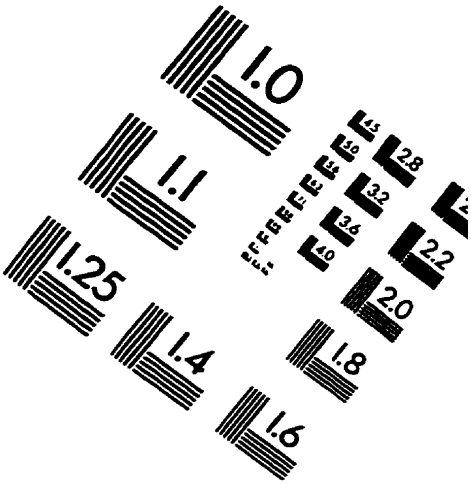
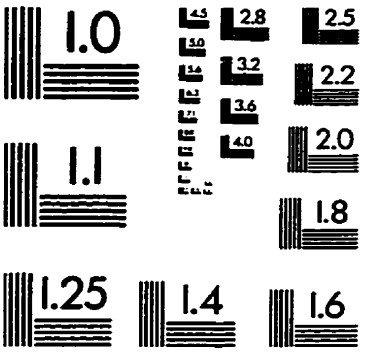
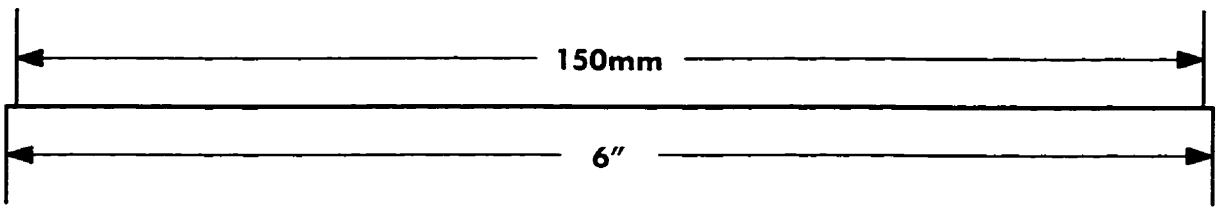


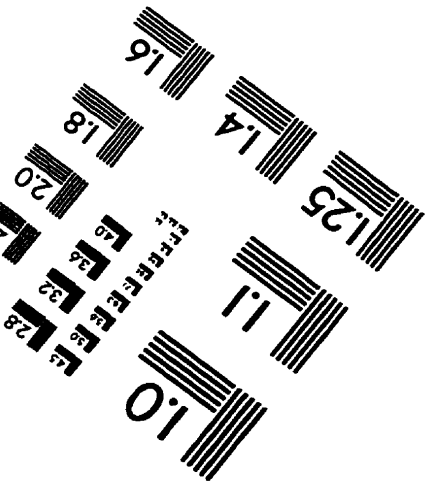
IMAGE EVALUATION
TEST TARGET (QA-3)

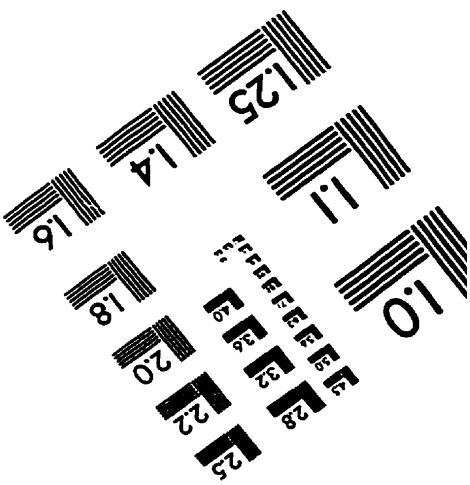












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