4-2006

Analysis of Factors Affecting Zebra Mussel (*Dreissena Polymorpha*) Abundance in Gull Lake, Michigan

Ryan P. Miller

ANALYSIS OF FACTORS AFFECTING ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) ABUNDANCE IN GULL LAKE, MICHIGAN

by

Ryan P. Miller

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Arts
Department of Geography

Western Michigan University
Kalamazoo, Michigan
April 2006

ACKNOWLEDGMENTS

First of all, I would like to thank my advisor, Dr. Chansheng He, for his assistance and guidance throughout the research process. From early advice about research topics and methods, to the final drafts, he made time for me every week to answer my questions and kept me on the right track. I would also like to thank my two other thesis committee members, Dr. James Biles, and Dr. Kathleen Baker for their help on the data processing, data analysis, and general advice during the research. I would also like to thank current and past graduate students in the Geography Department for their peer support throughout our time at WMU.

Thank you to Dr. Orlando Sarnelle and Dr. Steven Hamilton at Michigan State University for the advice and for providing the zebra mussel data. I would also like to thank Lidia Szabo Kraft at the Institute for Fisheries Research of the Michigan Department of Natural Resources for the Gull Lake shapefiles.

Finally, I would like to thank my mother, father, sister, grandfather, and grandmother for their support and patience throughout this process. Thank you for your patience and advice. I couldn't have done it without you!

Ryan P. Miller

ANALYSIS OF FACTORS AFFECTING ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) ABUNDANCE IN GULL LAKE, MICHIGAN

Ryan P. Miller, M.A.

Western Michigan University, 2006

Zebra mussel (*Dreissena polymorpha)* proliferation has become a serious problem in the Great Lakes Basin. This study uses bathymetry, vegetation distribution, and substratum data to assess their relationship with zebra mussel measurements in Gull Lake, Michigan. Different statistical tests were performed in order to investigate the relationship between the variables and to infer any significance among the variables in relation to zebra mussel abundance. *Dreissena polymorpha* data include 16 sites on Gull Lake, collected in July of 1999. Vegetation, substratum, and bathymetric datasets were obtained and analyzed by using Geographic Information Science (GIS) techniques.

Analysis of variance (ANOVA) concluded that the average size of zebra mussel was significant ($P = .026$, $\alpha = .10$) between the depths of 5 and 10 meters. Tests show that the average size of zebra mussels decreases with depth. Chi-Square Analysis revealed there was a significant relationship between depth, substrate type, and the number of zebra mussels. There was also a significant relationship between substratum type, vegetation type, and the number of zebra mussels. Chi-Square also exposed a significant relationship between depth, vegetation type, and the number of zebra mussels. Although this research only provides a microcosmus of the vast area of Gull Lake's zebra mussel population, its findings may be applicable in other inland lakes as well.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Background

Dreissena Polymorpha (zebra mussel) has invaded many lakes in the Great Lakes Basin of the United States, causing several adverse effects on the environment. The small bivalve is common throughout most of Europe and historically native to the Black, Caspian, and Azov seas (Griffiths *et al.* 1991). In Europe, *Dreissena* is a well-known biofouling organism that can disrupt the operations of water treatment and electrical generating facilities, negatively affect native species populations, and alter the energy and nutrient flow of aquatic ecosystems (Griffiths *et al.* 1991).

Invasive, introduced species have been defined as successfully reproducing organisms transported by humans into regions where they did not previously exist (Mills *et al.* 1993) with their success dependent on survival in unfavorable conditions, adaptability to new environments, high reproductive capacity, and the ability to disperse. Zebra mussels were introduced to the Great Lakes Basin around 1988 in Lake St. Clair by means of ballast water from ocean going vessels originating in Europe (Herbert *et al.* 1989). Since then, the mollusk has spread to many of the inland lakes and river systems in the United States. By 1991, 3 years after their initial detection, zebra mussels were already found throughout the Laurentian Great Lakes and connecting river systems as far away as Louisiana and Quebec (Kraft and Johnson 2000). Although many other potential mechanisms exist, the overland transport of recreational boats is widely believed to be the primary vector for zebra mussel dispersal into inland lakes (Bossenbroek *et al.* 2001).

Mussels possess a suite of ecological and life history characteristics that are unusual for freshwater benthic species including high rates of filter feeding, high fecundity, dispersible veliger (planktonic larvae), and attachment to hard substrates (Padilla *et al.* 1996). Mussel invasion has had many negative economic and biologic implications such as biofouling (clogging of water intake pipes by attaching *Dreissena*), dramatically changing water turbidity/clarity, and the displacement of native clams (Herbert *et al.* 1989). Zebra mussels have become the first invader in North America to foul municipal water systems and power plant plumbing. The cost of repair and remediation in the state of Wisconsin was estimated in 1994 at $4 million (Padilla *et al.* 1996). The most dramatic ecological effects of zebra mussels reported to date have been reductions in phytoplankton biomass and turbidity and local extirpations of native mussel populations (Raikow *et al.* 2004). Forecasting the effects of zebra mussels on ecosystems yet to be invaded is currently limited by, among other things, the ability to predict the eventual abundance of *Dreissena* (Wilson and Sarnelle 2002).

According to Bially and Macisaac (2000), zebra mussels live on average about four or five years. For reproduction to occur, the temperature of the water needs to be at least 12 °C where the females can start to release their eggs to be fertilized by the males (Bially *et al.* 2000). A mature female usually produces 30,000 to 40,000 eggs a year, however, females can lay up to 1,000,000 eggs a year when the stable water temperature extends the length of the breeding season (Bially *et al.* 2000). Once the breeding has concluded, the eggs go through many stages before they become adults, which can be seen in Table 1. According to Bially *et al.* (2000), most young mussels die if they fail to locate suitable substrate upon which they settle and secure byssal threads. Following

Dreissena's initial introduction into Lake Erie, populations on hard substrate grew explosively, with mussel densities approaching 30,000 per m^2 on all hard surfaces with maximum mussels densities exceeding 300,000 per m^2 (Haltuch and Berkman 2000).

Table 1: Zebra mussel life cycle (Sloane, *et al.* 1999)

STAGES	**DESCRIPTION**
Preshell Larva	The shell has not formed yet
Veliger Stage	Velum develops, which is organelle used for feeding
Straight-hinged Larva	The first time the shell is all around the internal organs
Ilmbonal Larva	The shell is not transparent anymore
Post-Veliger Stage	Time after the velum has finished developing
Pediveliger	Has foot to help it move, and the shell is thicker and whiter
Planti Grade	Last stage as a larva, the shell has elongated, siphons form
Settling Stage	Mussel done making organs, gills, siphons, byssal threads

Geographic Information Science (GIS) has been used as a tool in many studies focusing on zebra mussels. Most of such studies to date have focused mainly on identifying the habitat for zebra mussels (Chakraborti *et al.* 2002). Haltuch *et al.* (2000) used GIS for interpreting the expansion of nonindigenous species. Three data layers were created for spatial analysis including Lake Erie bathymetry at 1 m contour intervals, composition of Lake Erie substrates, and side scan sonar (SSS) data from 1994-1998. Furthermore, the study demonstrated that the distribution, abundance, and ecosystem impacts of invasive species in other watersheds can be accurately described and interpreted over diverse spatial and temporal scales using GIS models. Chakraborti *et al.* (2002) developed three layers of attributes from the variables of temperature, phytoplankton biomass, and total suspended solids, which were then overlaid in a GIS environment according to their respective weighting factors. Their study showed that the GIS-based statistical model provides a rapid, reliable, and cost effective tool to prioritize locations of *Dreissena* growth.

Statistical techniques have been widely used in a variety of studies. In the study done by Haltuch *et al.* (2000), multiple regression analysis of ecosystem data (depth, substrate type, survey year, and side scan sonar (SSS)) were used to predict percent cover of *Dreissena*. Among the variables, however, only year, mud, sand/mud, sand/gravel, and bedrock were significant contributors to the estimation of *Dreissena* percent cover (Haltuch *et al.* 2000). Wilson *et al.* (2002) developed a multiple regression model for predicting zebra mussel biomass from summer epilimnetic total phosphorus (TP) using published data from Polish lakes. The model was used to predict *Dreissena* biomass in six recently invaded North American lakes (Wilson *et al.* 2002). The results revealed that the predictive relationship for the combined Polish and North American data is useful as a first step for predicting zebra mussel impacts, as well as for estimating reasonable stocking densities of zebra mussels for in situ experiments.

Problem Statement

A number of lake characteristics may influence the biomass of zebra mussels in freshwater lakes, including: lake depth, bottom slope, substrate type, degree of mixing, turbidity, nutrient concentrations, and phytoplankton biomass (Wilson *et al.* 2002).

Different studies have examined a variety of inland lake characteristics that were believed to affect zebra mussel infestation (Raikow *et al.* 2004, Chakraborti *et al.* 2002). These studies analyzed the effects and consequences of mussel abundance throughout the inland lake ecosystem, but have not focused on the factors that support their abundance. This study will use zebra mussel measurements, bathymetry (water depth), vegetation type, and substrate type as important variables affecting the abundance of zebra mussels in Gull Lake, Michigan.

The purpose of this research is to examine the relationships between location, bathymetry, substratum and vegetation type, and various zebra mussel measurements. The zebra mussel measurements include size class, raw count, dry mass, biomass, average size per class, and total counts per site. A total of 16 sites were examined on Gull Lake at 4 random depths of 2.5, 5, 7.5, and 10 meters. Nine main substrate types are present in Gull Lake including fibrous peat, fibrous peat and sand, gravel, marl, marl and muck, marl and pulpy peat, pulpy peat, sand, and sand and marl. Studies in other lakes have found that zebra mussel abundance and substrate type are directly related. Therefore, their relationship will be examined in Gull Lake to compare to the results of others. Bathymetric measurements will be considered in this research as well. Vegetation has been shown to be an important variable by Neng and Culver (1999) that macrophytes and zebra mussels have about the same distribution, and their biomasses are positively related. Three vegetation types (submergent, emergent, and floating) will be examined in this research to determine if their relationship with zebra mussel measurements is significant. In order to address the relationship between these variables and zebra mussels in Gull Lake, three key research questions are to be addressed:

1) Is there a relationship between bathymetry and the average number and size of zebra mussels?
2) Is there a relationship between substrate type and the average number and size of zebra mussels?
3) Is there a relationship between vegetation type and the average number and size of zebra mussels?

Purpose of the Study

This study investigates the spatial relationship between a set of bathymetry, substrate, and vegetation variables and the growth of zebra mussels in an inland lake. The objective of this research is to use a number of statistical techniques to examine the relationship between lake characteristics and the zebra mussel measurements. Different statistical tests including a Chi-Squared and Analysis of Variance (ANOVA) test are used to asses the significant relationships between the different variables.

Multiple data sets were acquired from various sources including the Kellogg Biological Station of Michigan State University and the Institute for Fisheries Research of the Michigan Department of Natural Resources. Researchers at the Kellogg Biological Station of Michigan State University collected zebra mussel density and biomass measurements in July of 1999. Dr. Orlando Sarnelle of Michigan State University graciously provided these data to me. Vegetation, substratum, and bathymetric datasets were obtained from the Institute for Fisheries Research of the Michigan DNR digital water atlas. GIS are used to process and analyze the DNR data layers to test for correlation between them and the different mussel density and biomass measurements.

The Study Area

Gull Lake is located about 46 miles east of Lake Michigan lying in Kalamazoo and Barry counties (see Figure 1 and Figure 2). The surrounding topography is rolling to hilly, wooded, and is dominated by glacial features (Downing 2003). Gull Lake's surface area is estimated to be 2,030 acres (Taube and Bacon 1952). A major part of the lake is over 40 feet deep (12 meters) with the deepest points reaching 108 feet deep and 110 feet deep (30 and 33 meters). The lake contains an island at the southeast end that can clearly be seen in Figure 2. A small dam is also located at the southern end of the lakeshore where the Gull Lake outlet begins, but it has a minimal influence on the depth of the lake (Marsch 2003). In addition, Gull Lake has three outlets at Miller, Little Long, and Wintergreen Lakes (Downing 2003). It is a recreational lake with public access (Moss 1972). The surrounding land-use is primarily residential with the exception of the Kellogg Biological Station (a research facility of Michigan State University), Gull Lake Bible Conference, Gull Lake Marina, Gull Lake Country Club, and several municipal parks along the shoreline (Downing 2003).

The lake bottom is comprised of shoal, sand, gravel, till, marl, and peat. Gull Lake's temperatures are between 75 – 80 °F on the surface during the summer, but chill off to 45 – 50 °F when descending 30 feet below the surface (Marsch 2003). The lake water also "turns over" twice a year, with the mixing of the water layer occurring each autumn and spring. The lake is considered to be slightly mesotrophic with high water quality. Gull Lake's water is bluish-green in color due to the high concentrations on calcium and magnesium salts (Tessier 2001).

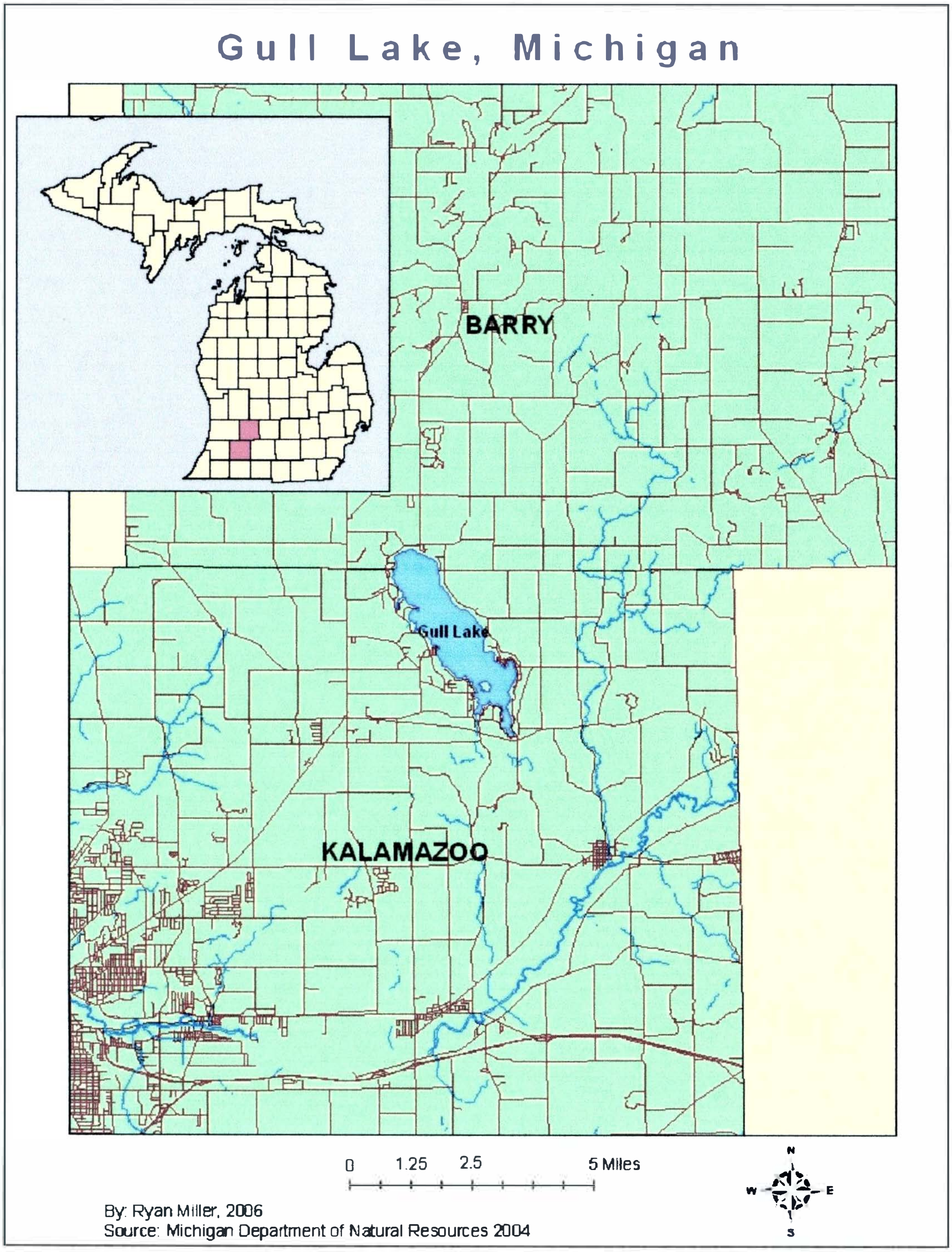

Figure 1: Location of Gull Lake in Kalamazoo and Barry Counties, Southwestern Michigan

Figure 2: Gull Lake, Michigan (Source: Michigan Department of Natural Resources 1998 DOQ)

Organization

This study first reviews literature on zebra mussels specifically in terms of the physical factors of bathymetry, substratum, and aquatic vegetation (Chapter II). The background physical information also includes important historical information on Gull Lake. Subsequently, Chapter III discusses methods and procedures used throughout the research process, including the GIS and statistical techniques that were used. Chapter IV provides results and discussion based on the GIS and statistical analysis of the data. Summary and conclusions are discussed in Chapter V based on the results, along with limitations and recommendations for future research.

CHAPTER II

LITERATURE REVIEW

Several researchers have investigated zebra mussels in a broad range of studies. Most studies have focused on identifying the land cover or habitat of the mussels. Some researchers have created statistical models that predicted zebra mussel coverage in a body of water. Substratum type has been the focus of many researchers, while others have looked at different variables that investigate the spatial relationship between limnological variables and zebra mussels. Many of the studies on substratum have been located in Lake Erie. Also, bathymetric measurements have shown to be an important factor in relation to zebra mussel distribution or abundance. Moreover, vegetation specie and density have been studied by researchers to show a relationship with the movement or abundance of zebra mussels. This literature review will first highlight studies regarding the relationship between zebra mussels and substratum types. It then will look at depth as a factor affecting zebra mussel abundance. The final section will cover research dealing with vegetation and how it effects zebra mussel proliferation.

Substratum

The role of substratum stability in determining zebra mussel load on unionids (freshwater mussels) was analyzed by Toczylowski *et al.* (1999). The results indicate that substratum conditions are often critical in determining the relative zebra mussel loads that accrue on unionids. On stable and relatively hard lake/river bottoms, zebra mussel loads on unionids tend to be similar to those on other hard substrata. However, on bottoms mostly composed of very soft or unstable substrata, discrete hard objects become silted-over or buried, hence suboptimal for zebra mussels. The researchers concluded that high zebra mussel loads on unionids relative to other substrata are not a matter of preference for or attraction to the unionids, but are the outcome of differential survival/emigration of the *Dreissena* due to unstable or changing bottom conditions.

Mellina and Rasmussen (1994) described zebra mussel distribution along the St. Lawrence and Hudson rivers and in Oneida Lake, New York by using scuba divers and an in situ method of quantifying substrate characteristics. Empirical models were created for their abundance using the variables of substrate, temperature, depth, secchi depth, pH, conductivity, calcium, and TP (Total Phosphorus). The results indicate that calcium concentrations of 15 mg/l or less limited the distribution of zebra mussels. The entire south shore from Cornwall, Ontario to Ile d'Orleans, Quebec was colonized by zebra mussels wherever suitable substrate was found. Among the three systems, substrate size explained between 38 and 91% of the variability in density. The distribution of zebra mussels was also studied by Karatayev *et al.* (1998) who looked at the physical factors that limit the distribution and abundance of zebra mussels. Results indicated that zebra mussels require at least 25 % oxygen saturation, although they can survive several days in anaerobic conditions. The upper temperature limit for zebra mussels is around 32-34°C. The researchers also found that zebra mussels are most abundant on hard surfaces, particularly rocky surfaces, and on macrophytes. The factors that had the highest affect on distribution include suitable substrate, low oxygen stress, and low temperatures. Rocks, coarse sand, shelly sediments, silty sand, and submerged portions of macrophytes were considered suitable substrates for *Dreissena polymorpha.*

Large populations of the exotic rounded (noncarinate) shelled mussel of genus *Dreissena* were studied by Dermott and Munawar (1993) throughout the central and eastern basins of Lake Erie. Results showed that two different phenotypes were present on fine sediments (<150 μm) in the eastern basin. An elongated white morph was common on the profundal sediments beyond 40 m depth, while the quagga mussel was common on sand and sandy silt at depths between 10 and 30 m. Together with the carinated zebra mussel *Dreissena polymorpha,* which is very abundant on hard substrates in the sublitoral region, at least 80% of Lake Erie's bottom sediments have been invaded by *Dreissena*. Another study done in Lake Erie by Bially and Macisaac (2000) examined Lake Erie to determine whether colonization residency on soft sediments by introduced, fouling mussels (zebra mussels) were affected by physical disturbance. The results indicate that colony density was typically higher at moderate depths than at shallower and greater ones. Mussel-sediment habitat supported between 462 and 703% more taxa, and between 202 and 335% more individuals that adjacent soft-sediment lacking mussels. The results also show that physical disturbance directly limits the distribution of mussels on soft sediments, and the diversity and abundance of other benthic invertebrates in consequence.

Coakley *et al.* (1997) quantified the density and the distribution patterns of zebra mussel colonization in the western Lake Erie basin as a first step in investigating the effect on sediment properties of such an abrupt change in benthic community structure. Underwater video imagery and diver-collected samples were taken from representative offshore areas. The results indicate colonization levels of up to 20,000 live mussels per m^2 in soft sediments where adults with shells >10 mm comprised 47%. Broad irregular mats were found in association with hard bottom (bedrock, boulders, or wreck and large debris). Another study done in Lake Erie by Mitchell *et al.* (1996) looked at the estimation of dreissenid densities at sites affected by warm water discharges into Lake Erie (Nanticoke, Ontario) to separate the effects of depth, substrate type, and temperature. The results showed that both the quagga mussel and zebra mussel species' densities increased with depth. In shallow waters, quagga mussel were more abundant that zebra mussels. Depth and rock surface (substrate) were both significant predictors of zebra mussel abundance. Depth explained 34.9% of the variation in quagga mussel counts among rocks. Rock surface area explained 10.7%, and the interaction between rock surface and depth explained a further 1.5%. Rock surface explained 13% of variation in zebra mussel numbers, while depth explained a further 18.5%. The effect of depth on zebra mussel was linear and there was no interaction between depth and rock surface area.

Koutnik and Padilla (1994) studied the prediction of spatial distribution of zebra mussels among inland lakes of Wisconsin using GIS. They used limnologic data from previous models to predict (i) absence or presence, (ii) categorical population density, and (iii) numerical abundance of zebra mussels in 194 inland Wisconsin lakes. The objective was to test for associations between predicted lake population density classes and three landscape-scale characteristics (surficial deposits, bedrock type, and US EPA developed ecoregions) that may affect limnological parameters. The results showed that (1) available lake monitoring data can be used to predict zebra mussel density for groups of inland lakes, (2) more information of North American lakes with zebra mussel is required to reduce the uncertainty of the models, and (3) spatial analysis using GIS methods can provide valuable insight into the overall patterns of the potential spatial distribution of Dreissena.

Chakraborti *et al.* (2002) also used GIS to develop a statistical model to investigate the spatial relationship between limnological variables and the growth of zebra mussels in Saginaw Bay, Lake Huron. The presence of suitable substrate was an important factor for zebra mussel habitat, making inner Saginaw Bay an area of high mussel abundance. Measurements in Saginaw Bay showed that zebra mussel densities were correlated with substrate quality. Temperature, phytoplankton biomass (measured as chlorophyll a), and total suspended solids (TSS) as food particles were considered to be the most important limnological variables affecting growth of zebra mussel. The shallow portions of the inner bay and the areas in proximity to the shorelines were found to be the most suitable growth regions.

Haltuch *et al.* (2000) used GIS analysis with bathymetric, substrate, and side scan sonar (SSS) data to assess both spatial and temporal expansion of exotic dreissenid mussels onto sedimentary habitats in Lake Erie. These data were used for developing multiple regression models with substrate types and SSS data to interpret the expansion of *Dreissena* assemblages across the central and western basins of Lake Erie from 1994 to 1998. The results indicated that *Dreissena* coverage ranged from <1% on muds in 1994 to 67% on sands and gravels in 1997. Based on all of the substrates, the 1994-1997 models indicate that *Dreissena* beds have been expanding since 1994 at 1,000 ± 6 km^2/yr and presently occupy 5,484 ± 32 km^2 of the 25,734 km^2 sedimentary bottom of Lake Erie. The results indicated that expanding *Dreissena* beds are altering soft-substrate habitats and influencing the ecosystem dynamics throughout Lake Erie.

Bathymetry

Fleischer *et al.* (2001) studied that lake-wide distribution of *Dreissena* in Lake Michigan in 1999 with a bottom trawl survey. The survey was performed at depths of 9 to 110 m at each of seven index sites around the lake. The results showed that *Dreissena* biomass ranged from about 0.6 to 15 kg/ha at the various sites in 1999. The highest zebra mussel biomass was recorded at Frankfort, Michigan, and the lowest at Sturgeon Bay, Wisconsin. Zebra mussels were found at depths of 9 to 82 m at all sites, with their peak biomass at 27 to 46 m. The changes in the spatial distribution and population structure of *dreissennid* mussel populations in the lower Great Lakes were studied by Mills *et al.* (1999). The westward range expansion of quagga mussel into western Lake Erie and toward Lake Huron was investigated and the shell size, density, and biomass of zebra and quagga mussel with depth in southern Lake Ontario in 1992 and 1995 were compared. Results indicated that mean shell size of quagga mussel was generally larger than that of zebra mussel except in western Lake Erie and one site in eastern Lake Erie. In 1995, the zebra mussels were most abundant at 15 to 25 m whereas the highest numbers and biomass of quagga mussel were at 35 to 45 m.

Depth effects on zebra mussel reproduction were studied by Mantecca *et al.* (2003). Twenty samples of male and female *Dreissena polymorpha* in Lake Iseo, northern Italy, were studied from March 1999 to September 2000. Scuba divers brought up rocks covered with zebra mussels from about 2 and 25 m depths. The results showed that a water temperature of 12°C and phytoplankton blooms triggered spawning. Some mussels at 25 m depth always had active gonads, and reproduction continued all year with no seasonal gametogenic phases. The reproductive behavior of 25 m deep zebra mussels differed significantly from that of those in shallow water, where an annual pattern was confirmed.

Direct settlement of mussels from the plankton to suspended ropes in the water column was investigated at Ninety Mile Beach, northern New Zealand by Alfaro and Jeffs (2003). Mussel spat-collecting ropes were placed at two sites (inside and outside of Ahipara Bay) and at three different depths. The results showed that smaller mussels (<.049 mm) were found to be more abundant at shallower depths (2 m water depth) in August of 2000 (2086 +- 403 mussels / 0.5 m ropes). Conversely, larger mussels (>1.0 mm) were found to be more abundant at greater depths (18 m water depth) in September – December (1704 +- 318 mussels / 0.5 m rope). Statistical comparisons for larger mussels in 1999 resulted in a significant relationship between mussel abundance and depth, and higher settlement inside versus outside the bay. Although higher mussels abundances were generally found at the site inside the bay, those differences were not strongly supported by statistical analysis.

Wilson and Sarnelle (2002) developed a multiple regression model for predicting zebra mussel biomass from summer eplilimnetic total phosphorus (TP) using published data from Polish Lakes: dry tissue biomass = $-10.8 + 11.0\log_{10}TP$, $R^2 = 0.19$, $P < 0.04$, $N = 24$. This model was used to predict *Dreissena* biomass in six recently-invaded North American Lakes. The researchers were only able to find sufficient literature data on three variables including depth (mean and maximum), calcium concentrations (Ca^{+2}), and total phosphorus concentration (TP; summer and spring). The results indicated that mean depth and maximum depth were highly intercorrelated, so mean depth was used in the regression analysis. There was only a marginally significant correlation between Ca^{+2}

and logTP ($r = 0.43$, $P = 0.09$, $N = 16$) and no significant relationship between mean depth and logTP ($r = -0.32$, $P = 0.13$, $N = 24$) in the Polish data. Stepwise multiple regression indicated that Ca^{+2} and mean depth had some statistically significant influence on mussel biomass in the data ($P > 0.3$). The results also indicated that Ca^{+2} levels were above 30 mg/L in every lake, which is above the minimum threshold for successful zebra mussel growth. Based on both Polish and North American data, they proposed that a *Dreissena* biomass in excess of ~ 40 g/m² is not sustainable in lakes.

Aquatic Vegetation

The effect of lake stratification on the survival, growth, and distribution of zebra mussels was investigated by Neng and Culver (1999) in Hargus Lake, Ohio. Zebra mussels were incubated in cages and suspended at different depths in the water column at both pelagic (max. depth = 12 m) and littoral (max. depth = 3.5 m) sites from April 18th to September 28th, 1994. No mussels survived to the end of the experiment in cages >5.5 m, whereas the highest survival rate (76%) occurred at 5 m depth where temperature and dissolved oxygen (DO) remained fairly stable for at least 3 months. The field study showed that the zebra mussel and macrophytes had about the same distribution and their biomasses were positively related. The results indicated that the maximum distribution depth of the naturally occurring zebra mussels was only 2.8 m, whereas the adult mussels could survive the entire stratification period when being artificially placed on the 3.5 m bottom, and young mussels could colonize the 3.5 m bottom if solid substrates were provided. The research concluded that the lack of substrate, rather than hypoxia, was the limiting factor of zebra mussel distribution above the 5 m depths in Hargus Lake.

Skubinna *et al.* (1995) studied submersed macrophyte communities and turbidity near shore from 1991 to 1993 to determine if more light resulting from colonization of zebra mussels into Saginaw Bay in 1990 corresponded with changes in macrophyte distribution. The results indicated that turbidity decreased ($P < 0.097$) at transects in northern littoral regions from 1991 to 1993. The relative abundance of submersed macrophytes increased ($P < 0.0001$) at all transects from 1991 to 1993, especially at transects where turbidity decreases significantly. The results demonstrate that even in a large well-mixed lacustrine environment, zebra mussels have the capacity to reduce turbidity sufficiently to allow submersed macrophytes to expand their distribution and abundance.

Musko and Bako (2005) studied the density, the body length-body mass relationships, and the biomass of *D. polymorpha* living on submerged macrophytes in the littoral zone at four sites of different trophic status in Lake Balaton (Hungary) from May to October 2000. The dominant submerged macrophyte was *Potamogeton perfoliatus* in May/June and July and *Myriophyllum spicatum* in October. The fresh biomass of submerged macrophytes ranged between 450.64 and 3,171.51 g/m^2, and dry biomass ranged between 61.54 and 381.31 g/m^2. Zebra mussel biomass in Lake Balaton varied widely between 0.35 and 1,106.55 g fresh mass with shell/m^2, between 0.01 and 50.96g dry mass with shell/m^2, between 0.09 and 260.39g fresh mass without shell/m^2, and between 0.002 and 6.490g dry mass without shell/m^2. The results showed that the density of zebra mussel significantly depends on the type of submerged macrophyte and on the water depth. The types of submerged macrophytes and water depth have significant additive and interactive effects on the length of the animals. Only the water depth determined significantly the biomass of the zebra mussel.

Similar to other studies focusing on lake characteristics and their relationship to zebra mussel abundance, this study focuses on the relationship between zebra mussel measurements and bathymetry, substratum, and vegetation types. A majority of the research completed on the relationship between substrate type and zebra mussel abundance has been located in Lake Erie (Dermott and Munawar 1993, Bially and Macisaac 2000, Coakley *et al.* 1997, Mitchell *et al.* 1996, Haltuch *et al.* 2000). These studies have found that more often zebra mussels settle on hard substrates (Dermott and Munawar 1993, Coakley *et al.* 1997, Mitchell *et al.* 1996, Haltuch *et al.* 2000). However, quagga mussels (freshwater mussels) have been found to more often settle on soft substrates (Mitchell *et al.* 1996). The relationship between depth and zebra mussel abundance was also found to be important by many researchers (Fleischer *et al.* 2001, Mills *et al.* 1999, Mantecca *et al.* 2003, Alfaro and Jeffs 2003, Wilson and Sarnelle 2002). Finally, the relationship between aquatic vegetation and zebra mussel abundance was also studied (Neng and Culver 1999, Skubinna *et al.* 1995, Musko and Bako 2005). The researchers found that aquatic vegetation distribution and specie type were important factors in the estimation of zebra mussel abundance (Musko and Bako 2005).

CHAPTER III

METHODS AND PROCEDURES

Data Collection and Manipulation

The data used for this research all come from secondary sources. Four different data types were used in this research, including zebra mussel measurements, bathymetry, vegetation distribution, and substratum data. The bathymetric, substrate, and vegetation data were provided by Lidia Szabo Kraft of the Institute for Fisheries Research of the Michigan Department of Natural Resources in Ann Arbor, Michigan. Researchers at the Kellogg Biological Station of Michigan State University took zebra mussel measurements on Gull Lake in 1999. Dr. Orlando Sarnelle of Michigan State University kindly provided these data to me for analysis in this study.

The zebra mussel data were collected from July 9th to July 20th 1999 on Gull Lake. Mussels were sampled within a 0.9 m^2 quadrat by a pair of scuba divers. The 16 sites (Figure 3) were selected by dividing the lake into squares and randomly selecting 4 squares at 4 depths: 2.5, 5, 7.5, and 10 meters (about 8, 16, 25, and 33 feet). Divers collected everything they could feel within each quadrat and the coordinates of each site were determined via Global Positioning System (GPS). All macrophytes were harvested within each quadrat and the mussels were sorted by sieving through 1 mm mesh, and then by hand. All the large mussels ($\geq$ 15 mm) in each sample were counted and measured. The small mussels were sub sampled by distributing the sample over the bottom of a

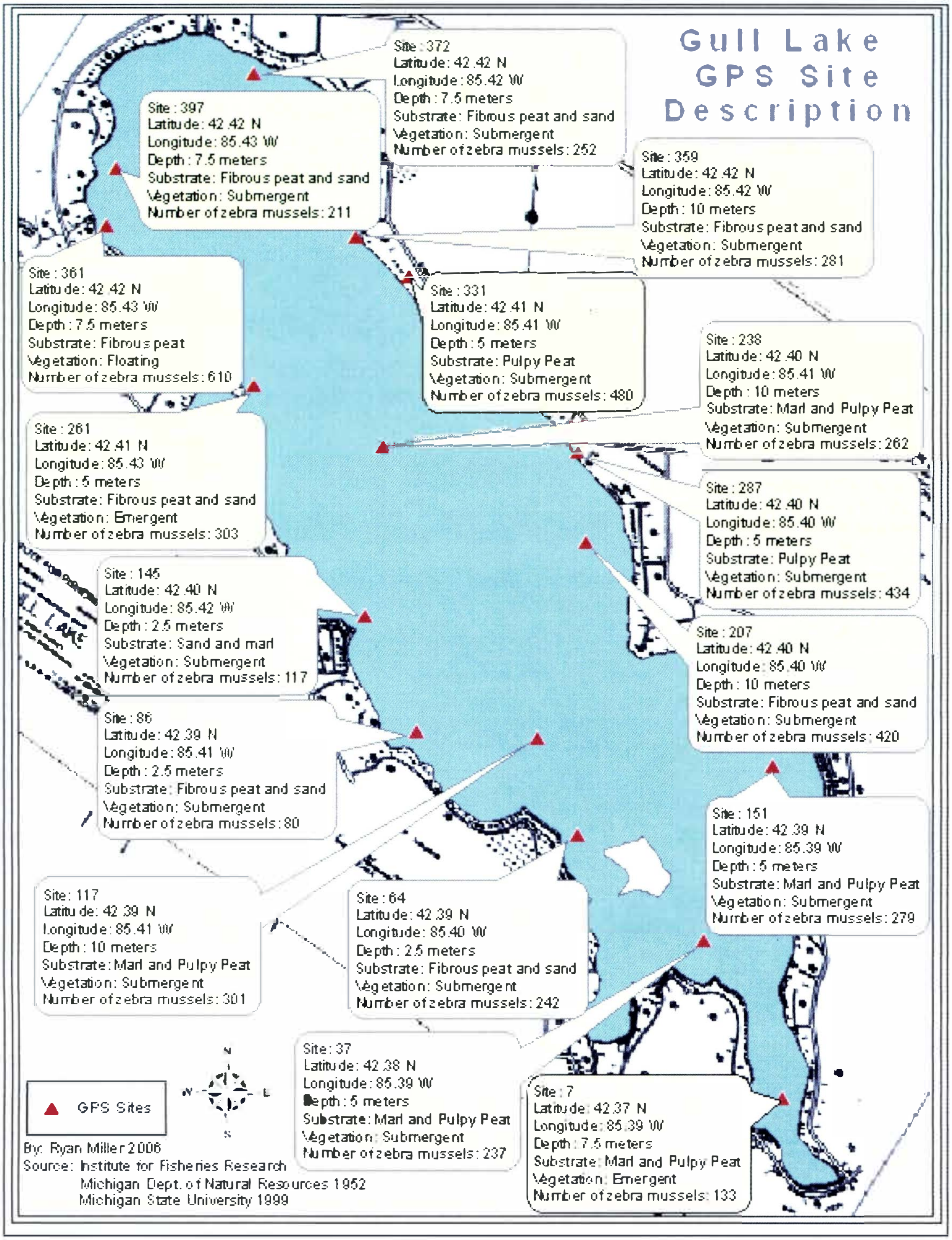

Figure 3: Description of the 16 sampling sites in Gull Lake

bucket, and placing three, 76 mm diameter pieces of pipe on the bottom on the bucket and collecting the mussels within each pipe. Each pipe piece represented 8.5% of the total area of the bucket. The sub sampling procedure was repeated to obtain a reasonable number of mussels for counting. A comparison of sub sample estimates with the entire-sample count for 2 samples showed that the sub sampling was accurate. Mussels on macrophytes were sub sampled by measuring the total weight of the macrophytes, and counting and measuring mussels within macrophyte sub samples of known weight (Sarnelle 1999).

Some sites had large numbers of very small mussels attached to macrophytes. In these cases, macrophytes were sub sampled by measuring the total wet weight of the macrophytes, then weighing out sub samples from which mussels were counted and measured. The researchers at MSU developed a dry tissue mass (g) versus shell length (mm) relationship from fresh Gull Lake mussels to convert size classes into biomass (g/m^2) (Wilson and Sarnelle 2002):

$$\mathrm{Log}_{10}\ \text{Dry Tissue Mass} = 2.5429 * \log_{10} \text{length} - 4.9396 \qquad (1)$$

$$(R^2 = 0.93,\ N = 50)$$

Variables including zebra mussel dry mass (g) and biomass (g/m^2), size class (mm), and raw count were important in the analysis process. The mussels were classified into different size classes according to their shell length. Zebra mussels that were from 0 - 4 mm in length were considered to be in class 1, from 5 – 9 mm in length class 2, 10 - 14 mm in class 3, and mussels that were $\geq$ 15 mm in length were considered to be in class 4. Once the classes were established, the raw count for each class was calculated. The mussel dry mass and biomass were then calculated according to size class as well. Along with these calculations, the total count for each individual site was computed. After that, the average size of the zebra mussels in each size class was determined using a weighted average function. This was done by multiplying the length of the mussel by the raw count for each size, then adding the products together and dividing by the total count for each individual size class. And finally, total mussel dry mass and biomass were computed for each of the 16 sites on Gull Lake.

Bathymetry is used to measure the depth of a body of water and for charting the topography as well. A bathymetric map was created from data provided by the Digital Water Atlas of the Michigan DNR (Szabo Kraft 1952) (see Figure 4). The bathymetric contours were assigned 2 meter intervals in ArcMap. The water in Gull Lake reaches impressive depths of around 30 and 32 meters (108 and 110 feet) in two separate areas of the lake. There is also another area just north of the island on the southern side of the lake that reaches around 26 meters (85 feet).

Substratum data were used to find bottom types suitable for mussel growth. Zebra mussels are attracted to hard bottoms so that they can attach themselves for feeding, reproducing, and other functions. Horvath *et al.* (1999) found that zebra mussels attached themselves to hard substrates in lakes and large rivers by means of their byssal threads that produce a glue-like adhesive. A map laying out the substratum types was generated using ArcMap (see Figure 5). Gull Lake's substrates were classified as fibrous peat, fibrous peat and sand, gravel, marl, marl and muck, marl and pulpy peat, pulpy peat, sand, and sand and marl. Gull Lake till is composed of material of all sizes, with marl and pulpy peat predominating along with fibrous peat and sand (Marsch 2003). The lake is limited by the sediments of fibrous peat and sand which are non copious. According to

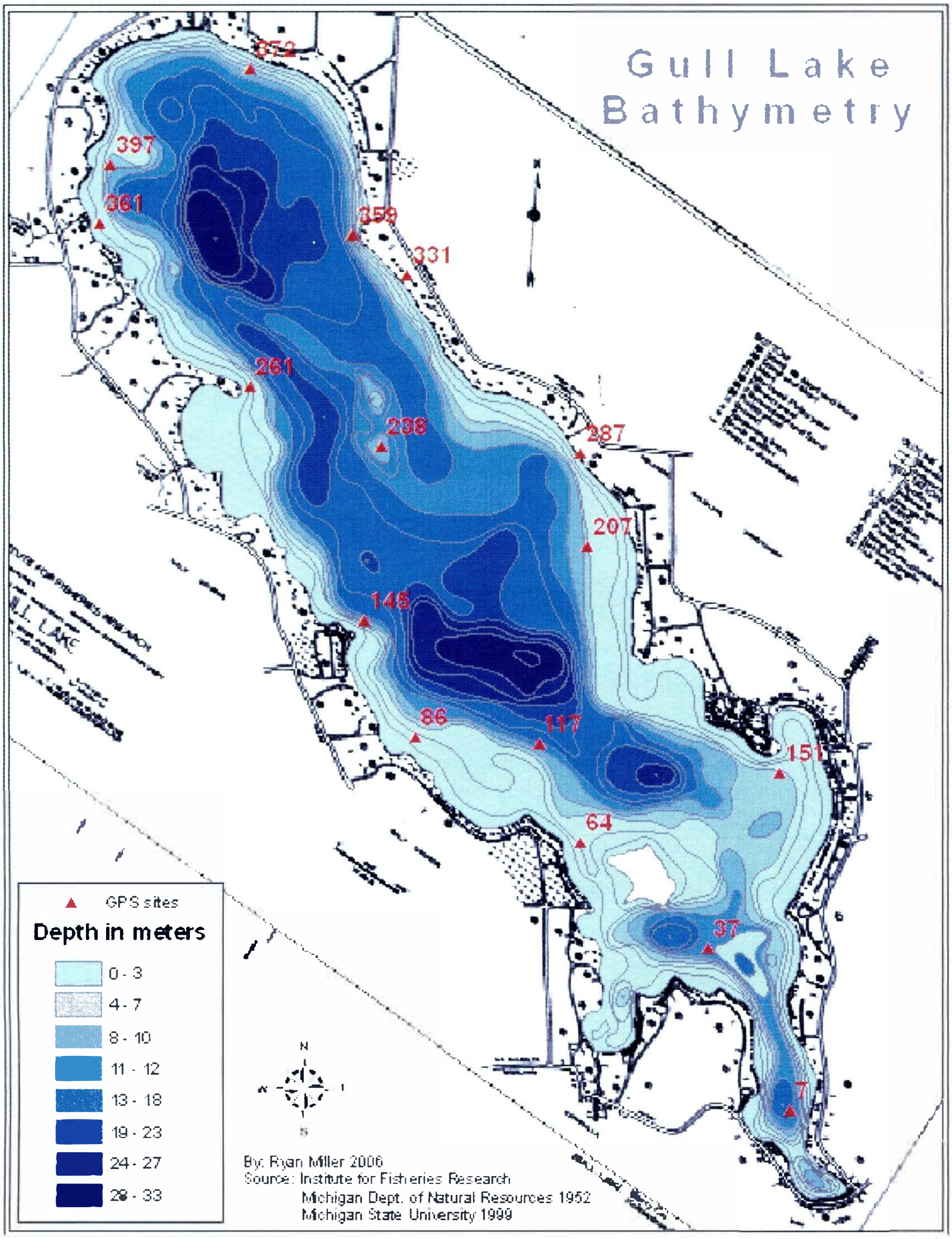

Figure 4: Gull Lake bathymetry with GPS sites

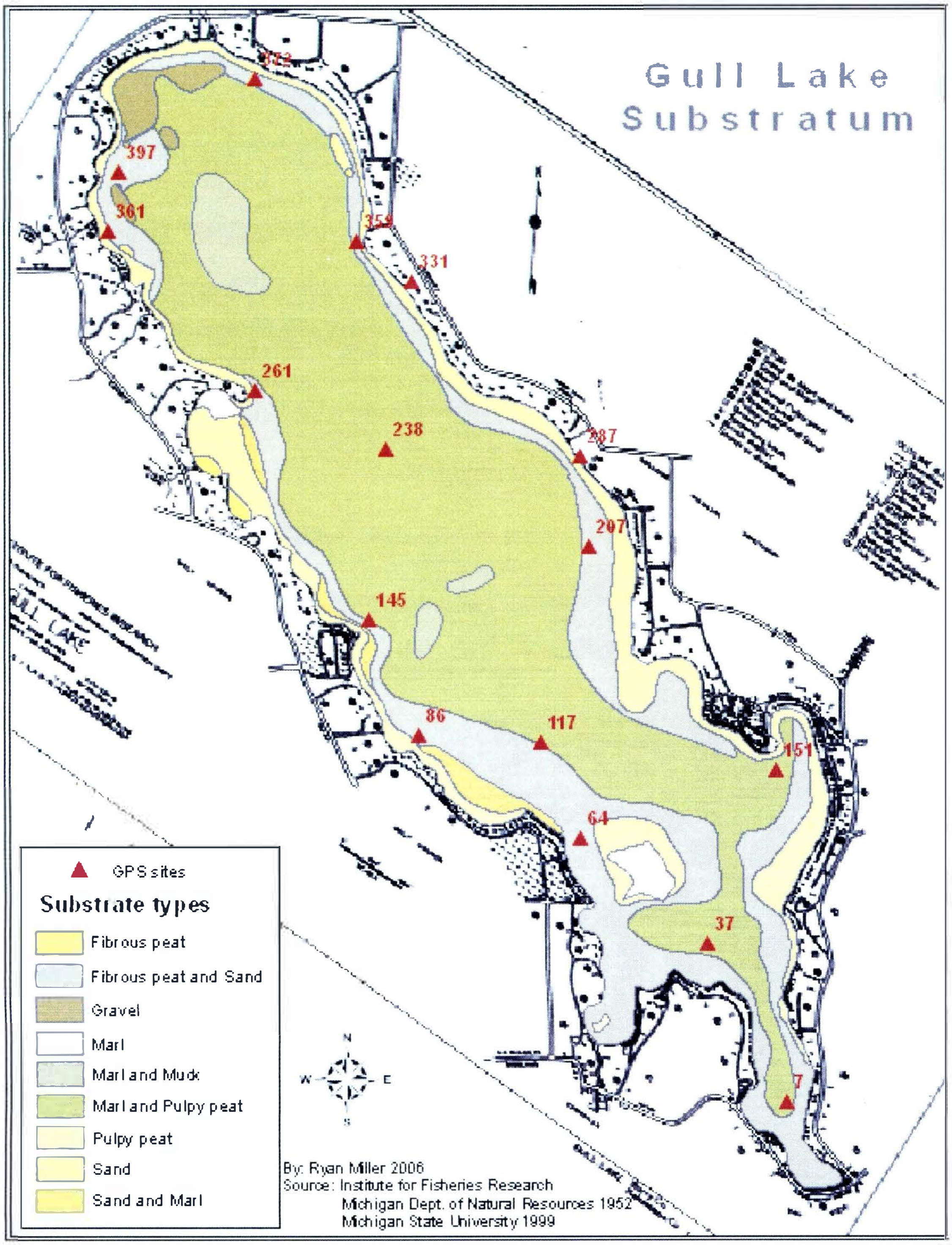

Figure 5: Gull Lake substrate types with GPS sites

Jackson (1997), peat is a dark-brown or black residuum by the partial decomposition and disintegration of mosses, sedges, trees, and other plants that grow in marshes and other wet places. Two types of peat that located in Gull Lake are fibrous peat and pulpy peat. Fibrous peat is peat in which original plant structures are only slightly altered by degradation of cellulose matter (Jackson 1997). Also, pulpy peat, or sedimentary peat, is formed under water, usually lacustrine, and consisting of mainly algae and related forms. Another sediment type located in Gull Lake is marl, which is a soft, grayish to white, earthy or powdery sediment usually consisted of calcium carbonate precipitated on the bottoms of present-day freshwater lakes (Jackson 1997).

Vegetation data were used in this research as a variable related to zebra mussel measurements. According to Neng and Culver (1999) macrophytes are important when looking at the relationship between vegetation and zebra mussels. Macrophytes are submersed aquatic vegetation that are a good indicator of the health of a body of water. Zebra mussels are often found attached to them. There are two basic types of macrophytes, which are littoral and sublittoral. Littoral macrophytes are submersed vegetation that are found along the shoreline of a body of water. Sublittoral macrophytes are submersed vegetation that are found between the shoreline and continental shelf of the ocean, or the drop-off of an inland lake. The vegetation data are composed of 586 individual points, each being identified as floating, emergent, or submergent in nature. In order to change the points into polygons, for research purposes, a proximity transformation needs to be applied. A Thiessen (Voronoi) polygon, which defines individual areas around each point, was created using ArcToolbox (Figure 6). The boundaries of a Thiessen polygon are created such that any location inside a polygon is

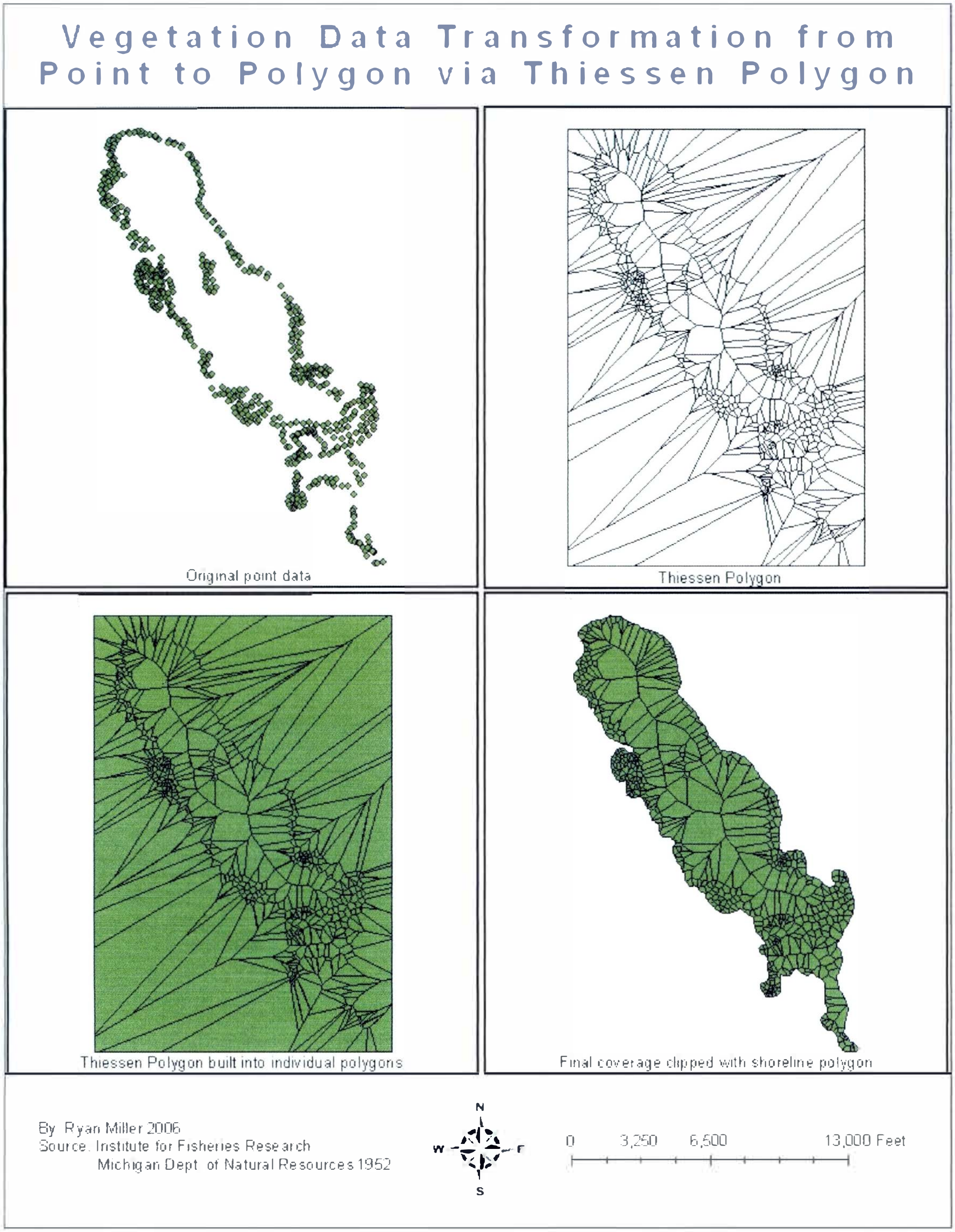

Figure 6: Vegetation coverage created by Thiessen Polygon

closer to that polygon's centroid than to any other polygon centroid (Fotheringham *et al.* 2000). Once the polygon is created, the edges are clipped using the clip tool in ArcToolbox so that the border of the lake could be preserved. This transformation allows for the vegetation data to be presented as separate polygons for further analysis. The vegetation data were used to create a representative map in ArcMap (see Figure 7).

GIS Analysis

Once the data were compiled and processed into appropriate format, they were then used for basic analyses. The shapefiles that were obtained from the Institute for Fisheries Research were used to create some basic informative maps. The bathymetry information was used to create a map along with the GPS points (Figure 4). This was also done with the substratum shapefile (Figure 5). The vegetation point data were transformed before they could be mapped out properly, which was explained earlier. After these manipulations were completed, an informative map was created containing the GPS points as well (Figure 7).

The zebra mussel data that were received from the Kellogg Biological Station contained four different depths measured in meters. The water depths in the bathymetry shapefile were in units of feet. Once the meter conversions were saved in the original shapefile, GIS was used to perform an Overlay Analysis of the different data layers. The distribution of sediment types at different depths was found by overalying the substrate and bathymetric layers. One type of overlay analysis is a union operation, which includes two different data layers that are combined to create a geometric intersection (Fotheringham *et al.* 2000). Another type of overlay analysis, which is used in this

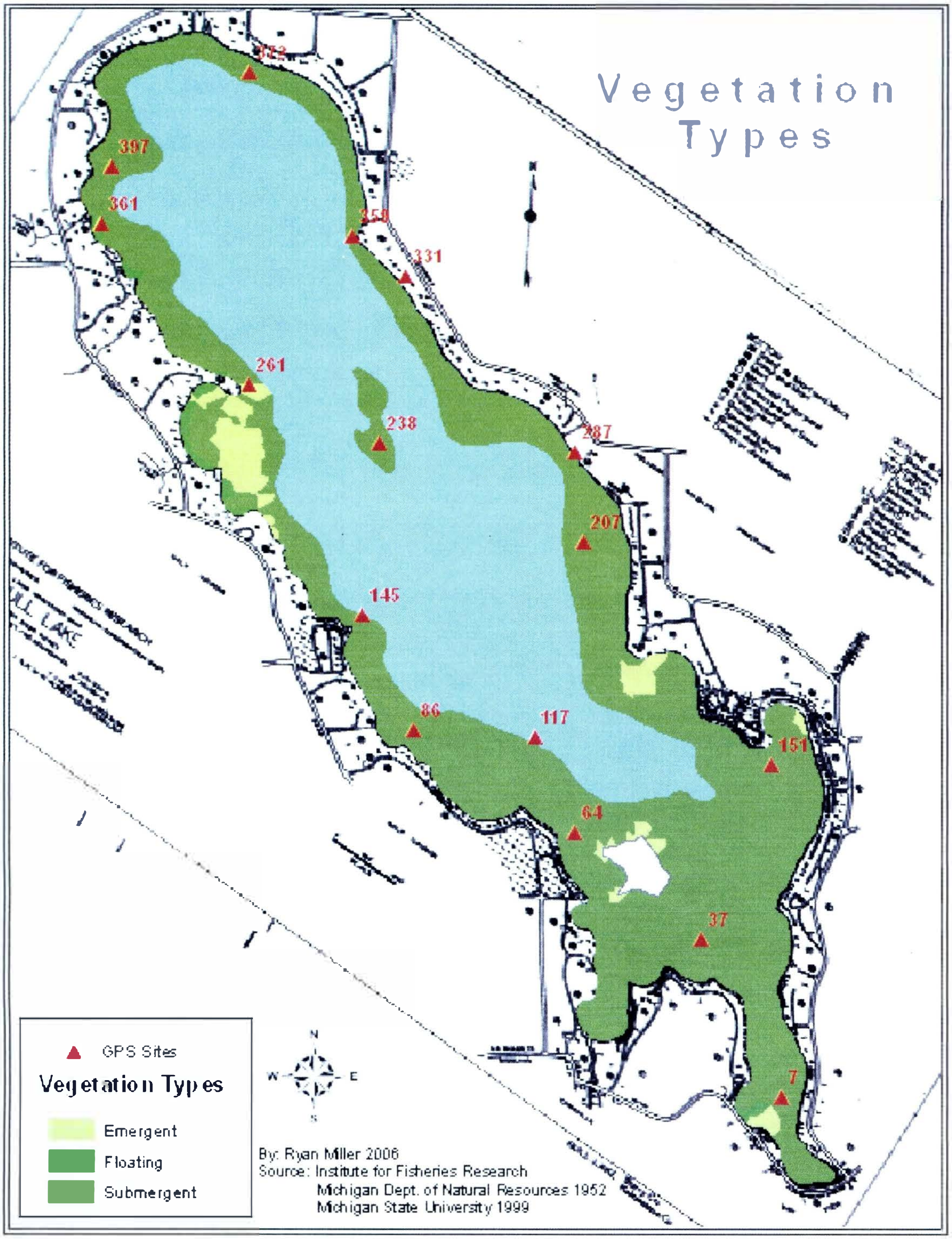

Figure 7: Gull Lake vegetation types with GPS sites

research is an intersection operation. According to Fotheringham *et al.* (2000), an intersection is an operation that may be carried out on polygon, line, or point data, the output coverage being of the same type as the input coverage. The new intersected layers were used to aggregate the sediment types together to determine the percent coverage of the sediments types at various depths.

Similar spatial analysis was done to create a coverage for the bathymetry and vegetation layers. More specifically, the intersect function was used to create the new coverages. The output coverage was used to determine the different vegetation types at various depths in Gull Lake. The output layers from the intersection were also used to decipher which substrate type was present at each sampling site. Also, the vegetation type was discovered at each sampling site with the output coverage. This information was used in the statistical analysis when comparing the different variables to determine their significant differences.

Research Hypotheses

The goal of this research is to evaluate the relationship between zebra mussel measurements, bathymetry, substrate, and vegetation type. In order to assess the relationship between these variables, a set of null hypotheses are described below:

Ho: The number of zebra mussels does not vary with depth.

Ho: The average size of zebra mussels does not vary with depth.

Ho: The number of zebra mussels does not vary with substrate type.

Ho: The average size of zebra mussels does not vary with substrate type.

Ho: The number of zebra mussels does not vary with vegetation type.

Ho: The average size of zebra mussels does not vary with vegetation type.

Ho: The number of zebra mussels does not vary between depth and substratum.

Ho: The number of zebra mussels does not vary between depth and vegetation.

Ho: The number of zebra mussels does not vary between vegetation and substratum.

The above hypotheses were analyzed using various statistical tests which are described in the following section.

Description of Statistical Tests

The statistical tests used in this study included a non-parametric Chi-Square and Analysis of Variance (ANOVA). Microsoft Excel and SPSS were used in the analysis of the variables. The dependent variables of the analyses are depth, substrate type, and vegetation type. The independent variables include the number of zebra mussels (count) and the average size of zebra mussels per size class. Table 2 shows an example of two of the GPS sites that were collected on Gull Lake. The confidence level for the Analysis of Variance test was set at 90%, or $\alpha = .10$. This significance level was chosen because of the small sample size. The significance level for the Chi-Square test was set at 95%, or $\alpha = .05$.

Chi-Square

One way that geographers can study spatial patterns is with a Chi-Square test. Chi-Square is a non-parametric test of statistical significance for bivariate tabular

Table 2: Examples of variables used in the research of Gull Lake

Site	Depth(m)	SubstrateType	Vegetation	Class	Count	DryMass(g)	Biomass(g/m²)	TotalCount	AverageSize(mm)
37	5	Marl and Pulpy Peat	Submersed	1	26	0.000622	0.009		3.731
37	5	Marl and Pulpy Peat	Submersed	2	142	0.008583	0.247		6.746
37	5	Marl and Pulpy Peat	Submersed	3	55	0.032517	0.365		11.618
37	5	Marl and Pulpy Peat	Submersed	4	14	0.55077	0.252	237	17
151	5	Fibrous Peat and Sand	Emergent	1	62	0.000622	0.078		3.548
151	5	Fibrous Peat and Sand	Emergent	2	149	0.008583	0.881		6.383
151	5	Fibrous Peat and Sand	Emergent	3	90	0.032517	2.299		11.544
151	5	Fibrous Peat and Sand	Emergent	4	2	0.55077	7.128	303	15

analysis (Conner-Linton 2003). It is useful in comparing multiple nominal variables against each other to determine significant differences (Marsch 2003). It is also more forgiving than parametric statistical tests in that it will accept more forms on data (Conner-Linton 2003). Although Chi-Square is forgiving, there are still some requirements. According to Conner-Linton (2003), the sample must be randomly drawn from the population. Secondly, data must be reported in raw frequencies and not percentages. Thirdly, the measured variables must be independent. Fourthly, values or categories on independent and dependent variables must be mutually exclusive and exhausted. And finally, observed frequencies cannot be too small (Conner-Linton 2003). The standard Chi-Square equation is:

$$X^2 = \sum \frac{(O-E)^2}{E} \qquad (2)$$

O = Observed Frequency
E = Expected Frequency
DF = Degrees of Freedom = (# of rows – 1) (# of columns – 1)

In terms of this particular research, Chi-Square is used to determine whether or not there were any significant differences among the variables of depth, substrate type, and vegetation type in terms of raw count of zebra mussels. There are three different types of vegetation and five different types of substrates that are applicable at the research sites. The degree of freedom and the level of significance ($\alpha = .05$) will be used along with the X^2 Distribution Table to find the critical value for the Chi-Squared tests. If the X^2 value is greater than the critical value (CV), then the relationship between depth, substrate type, and vegetation type when looking at the raw count of zebra mussels will be considered to be statistically significant and the null hypothesis will be rejected. On the other hand, if the X^2 value is less than the critical value, the null hypothesis will fail to be rejected, representing an insignificant relationship.

Analysis of Variance

According to Rogerson (2001) Analysis of Variance (ANOVA) represents an extension of the two-sample t-test for the differences of means. Variance is the average squared deviation of the observations from the mean. He also explains that there are some underlying assumptions of analysis of variance, as follows: (1) observations between and within samples are random and independent, (2) the observations in each category are normally distributed, and (3) the population variances are assumed equal. The test itself is carried out using two independent estimates of the common variance. One estimate of the common variance is a pooled estimate of the within group variances. The other estimate of the variance is a between group variance (Rogerson 2001). When the mean square value for the between group variance is larger than the within group variance, then there is a statistical significance.

Analysis of Variance is used in this research to test the significance between and within the various groups of variables. Using the three different dependent variables (factors), the test is run looking at the average count and average size of zebra mussels. Tukey's Post Hoc Test is used to determine which particular relationships are significant and which ones are not. The significance level was set at 10% ($\alpha = .10$).

CHAPTER IV

RESULTS AND DISCUSSION

GIS Results

GIS analysis of Gull Lake revealed that the lake has an area of about 2,030 acres. This measurement was consistent with the findings of Dexter (1996) and Taube and Bacon (1952). The lake also contains maximum depths of about 30 and 33 meters (108 and 110 feet) in two separate areas (Figure 4). This study focuses on the depth range from 2 to 10 m. A large portion of this area is in the littoral zone of the lake. The study area, between 2.5 and 10 m deep, accounts for about 35% of the lakes total area. The zebra mussel data collection took place at 4 depths. About 10% of the lake is around 2.5 m deep, 5% of the lake is 5 m deep, and the 7.5 and 10 m depths cover approximately .2% of Gull Lake. The average depth of data collection for all the sites was around 6.25 meters.

Since there were multiple polygons in the GIS substrate data (Figure 5), the sediment distributions for Gull Lake were found by summing the area of each polygon, and aggregating the sediment types together into one table. The individual distributions of sediments in Gull Lake were marl and pulpy peat, 55.76%; fibrous peat and sand, 24.12%; and pulpy peat, 12.62%; while fibrous peat, gravel, marl, marl and muck, sand, and sand and marl cover the rest of the area (Figure 8). Data on substrate types across the lake show that marl and pulpy peat and fibrous peat and sand were the most prevalent substrates.

Attention was given to the particle size of each sediment type in the study area in relation to the number of zebra mussels (Figure 9). The results showed that a smaller sediment size yielded a lower number of zebra mussels. Fibrous peat and sand (size 3) yielded that highest number of zebra mussels. The Udden-Wentworth Scale of 1922 was used to classify the different sediment types throughout Gull Lake. The scale ranges from the size of boulders to the size of clay. A large portion of Gull Lake's sediments fall between the category of sand and mud.

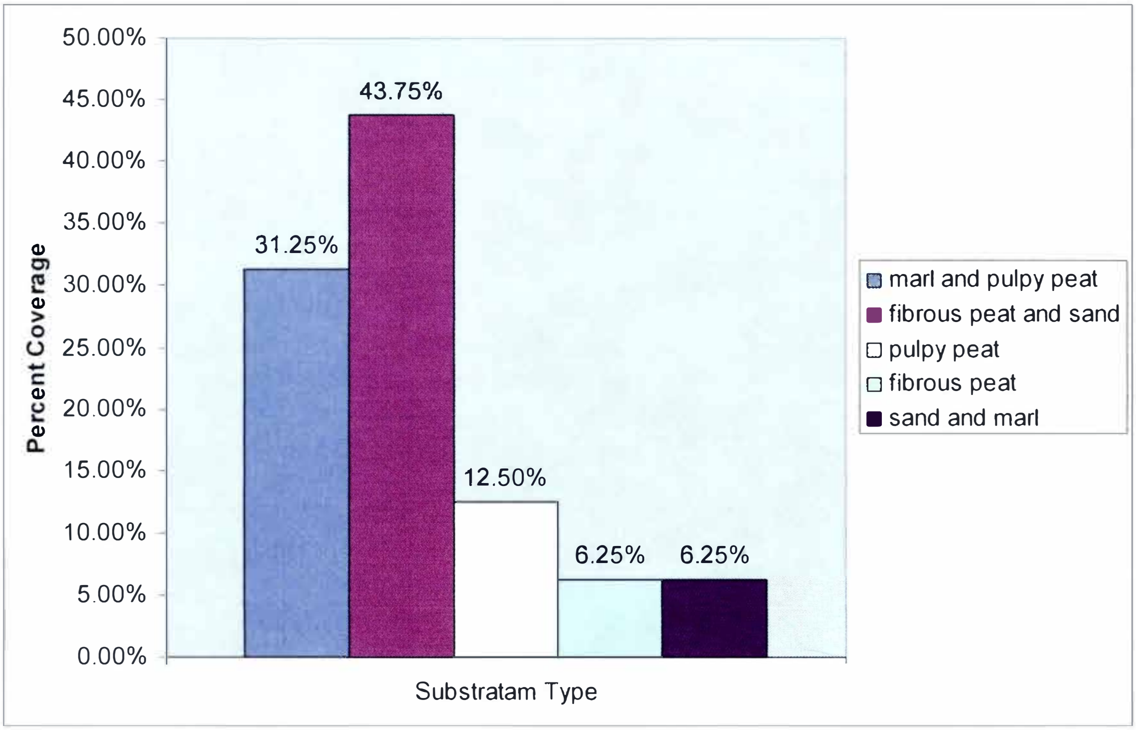

Figure 8: Distribution of substrates in the study area

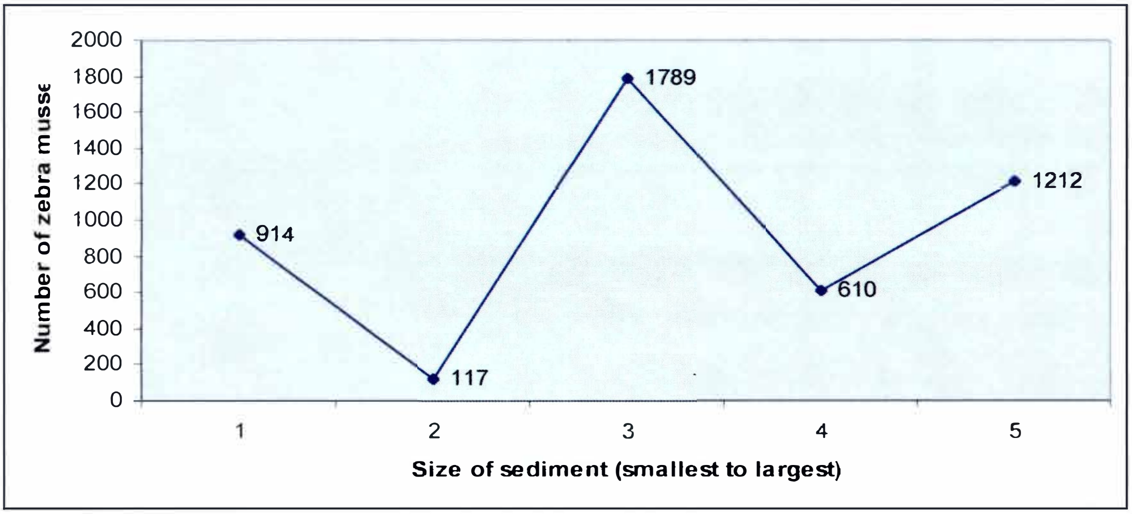

Figure 9: Relationship between sediment size and number of zebra mussels

The vegetation data was divided into three main types including emergent, floating, and submergent (Figure 10). The original vegetation data included 586 points throughout Gull Lake. In order to change the points into polygons for research purposes, a proximity transformation was applied. A Thiessen (Voronoi) polygon, which defines individual areas around each point, was created using ArcToolbox (Figure 6). The percent coverage of vegetation types were found in GIS by first aggregating the points into three main types, and then by summing the area of each polygon. The results showed that 12.50% contains emergent vegetation, 6.25% contains floating, and 81.25% contains submergent vegetation (Figure 10).

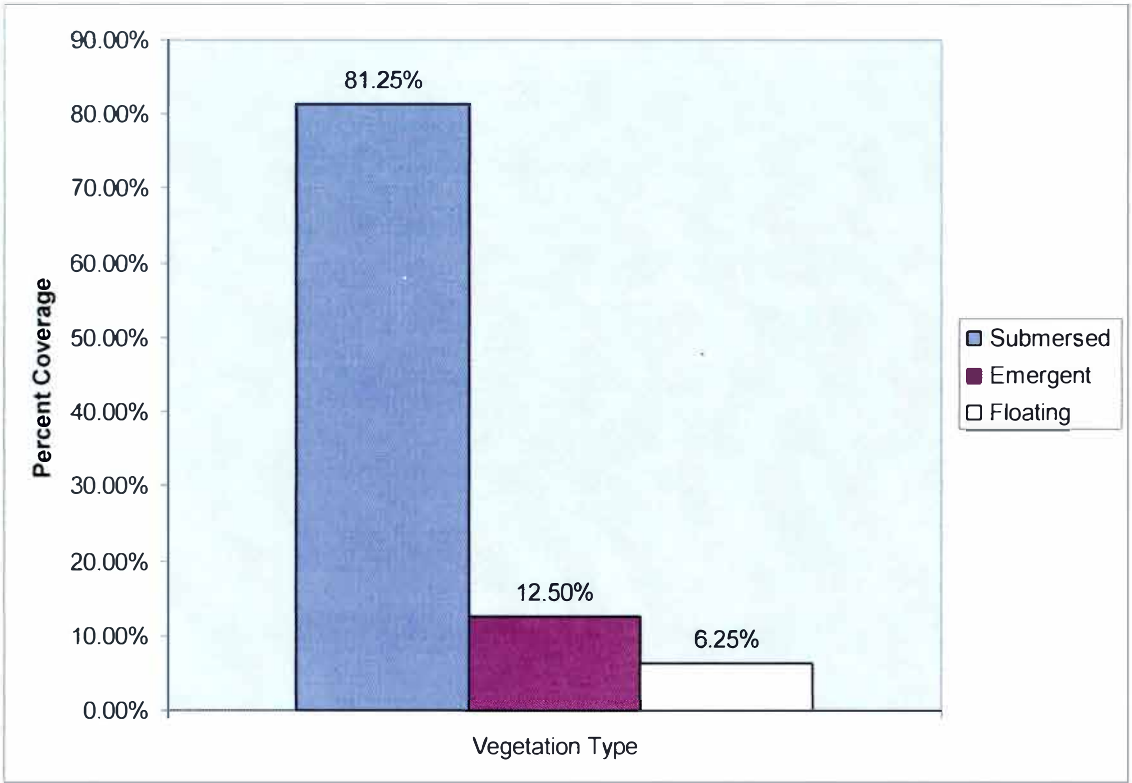

Figure 10: Distribution of vegetation within the study area

An intersect analysis was performed with the bathymetry and substrate layers. The results showed that marl and pulpy peat is the most prevalent sediment type (84.16%) with an average depth of around 16 m (Table 3). The next most prevalent substrate type is fibrous peat and sand (13.5%) with an average depth of 8 m. Another noteworthy sediment type is pulpy peat (1.493%), which has an average depth of 2 m.

Table 3: Distribution of substrate type and average depth in meters

Sediment Type	% Coverage	Average Depth (m)
fibrous peat	.0139%	4
fibrous peat and sand	**13.50%**	8
Gravel	.3019%	3
Marl	.0099%	0
marl and muck	.3203%	25
marl and pulpy peat	**84.16%**	16
pulpy peat	1.493%	2
Sand	.0211%	4
sand and marl	.1474%	2

The results indicated that sediments including gravel and sand are located in depths less than 4 m. These results are consistent with the findings of Dexter (1996) in Gull Lake that the shoal area, containing mostly sand, gravel, and rubble, was located in the area of the lake that is less than approximately 3 m deep.

Statistical Results

Descriptive Statistics

The first step in statistical analysis is to examine the descriptive statistics. Tables 4, 5, and 6 contain the descriptive statistics for the average number and average size of zebra mussels, depth, substrate, and vegetation type (the symbol "N" refers to sample size).

Table 4: Descriptive statistics by depth for zebra mussel count and average size

	Depth (m)	N	**Mean**	Std Dev	Min	Max
Average Number	2.5	16	**57.44**	79.106	0	287
	5.0	16	**78.31**	78.927	1	299
	7.5	16	**75.38**	159.485	0	601
	10.0	16	**79.00**	119.407	0	405
	Total	64	72.53	111.817	0	601
Average Size	2.5	16	**8.60**	5.155391	.000	16.956
	5.0	16	**9.50**	5.138638	3.495	18.000
	7.5	16	**5.44**	5.080709	.000	15.833
	10.0	16	**4.76**	5.113823	.000	18.107
	Total	64	7.07	5.395219	.000	18.107

When looking at the means, it is noteworthy that the average number of zebra mussels does not show a lot of variation except for the depth of 2.5 m. Also, when looking at the average size of zebra mussels at different depths, the standard deviation of the means do show little difference. It seems that when the depth increases, the average size of zebra mussels decrease.

Table 5: Descriptive statistics by substrate type for zebra mussel count and average size

	Substrate	N	**Mean**	Std Dev	Min	Max
Average Number	fibrous peat	4	**152.50**	299.014	0	601
	fibrous peat and sand	28	**63.89**	99.646	0	405
	marl and pulpy peat	20	**60.60**	69.774	0	224
	pulpy peat	8	**114.25**	122.254	1	299
	Sand and marl	4	**29.25**	27.753	2	68
	Total	64	72.53	111.817	0	601
Average Size	fibrous peat	4	**5.13**	5.418668	.000	12.500
	fibrous peat and sand	28	**5.84**	5.460039	.000	18.107
	marl and pulpy peat	20	**7.71**	5.252007	.000	17.000
	pulpy peat	8	**9.56**	5.174539	3.580	18.000
	Sand and marl	4	**9.47**	5.491996	3.522	16.000
	Total	64	7.07	5.395219	.000	18.107

As shown in Table 5, the means of the average number of zebra mussels vary greatly among each substrate type. It is apparent that the means of the average size of zebra mussels show some variation among substrate types as well. This dissimilarity among means is explained by the varying sample size of the substrate types. For example, the sample size of fibrous peat and marl and pulpy peat account for 75% of the samples. Alternatively, the sample size for the sand and marl sediment only account for 1/16 of the total sample.

The descriptive statistics for the vegetation type, when looking at zebra mussel average count and size, are shown in Table 6. Large variation exists among the means. Average number of mussels vary significantly where floating vegetation exists. Floating vegetation is existent at only one sample site in the study. The large standard deviation of the average number of zebra mussels located in floating vegetation is explained by the number of mussels (610) at this site. This particular site contained a lot of small mussels. Because of the lack of distinction between the means, it is necessary to examine the Analysis of Variance (ANOVA) to further explore the comparison of means.

Table 6: Descriptive statistics by vegetation type for zebra mussel count and average size

	Vegetation	N	**Mean**	St Dev	Min	Max
Average Number	Emergent	8	**54.50**	50.248	2	149
	Floating	4	**152.50**	299.014	0	601
	Submergent	52	**69.15**	96.305	0	405
	Total	64	72.53	111.817	0	601
Average Size	Emergent	8	**9.38**	4.896248	3.548	15.833
	Floating	4	**5.13**	5.418668	.000	12.500
	Submergent	52	**6.87**	5.455524	.000	18.107
	Total	64	7.07	5.395219	.000	18.107

Simple calculations provided insight into whether the average size of the zebra mussels varied over depth, substratum, and vegetation type. The average size of mussels located in emergent vegetation was the largest at 9.38 mm, while the average size of mussel in submersed vegetation (6.87 mm) was next, followed by floating vegetation (5.13 mm) respectively. Mussels located in emergent vegetation were larger in size on average in comparison to the other vegetation types. The average size of mussels does vary greatly with substrate type. Pulpy peat and sand and marl contained the largest mussels on average with sizes of 9.56 and 9.47 mm respectively. Fibrous peat contained the smallest mussels on average (5.13 mm). The sites that contain pulpy peat sediment have an abnormal amount of larger mussels in comparison to other sites. Focusing on the trend that mussel size decreases with depth, the small size of mussels located at sites with fibrous peat could be explained by the sediment being most abundant at deeper depths. Also, the pulpy peat sediment, being more abundant in shallower depths in Gull Lake, could explain the larger than average mussels located are there.

The average size of zebra mussels in relation to depth was also investigated (Figure 11) to see if there was any variation between the two. The results showed that the overall observed relationship is that mussel size decreases with depth. This is not consistent with the findings of Alfaro and Jeffs (2003) in New Zealand, where they observed that that smaller mussels (<.049 mm) were found to be more abundant at shallower depths (2 m water depth). Another inconsistency is that larger mussels (>1.0 mm) were found to be more abundant at greater depths in New Zealand (18 m water depth). This difference among studies may be explained by the duration of existence of zebra mussels in Gull Lake being much shorter than mussels in New Zealand. Mussels have only inhabited Gull Lake since 1994, while they have colonized New Zealand for much longer. The relationship between size of mussel and depth is explored further in the analysis of variance test.

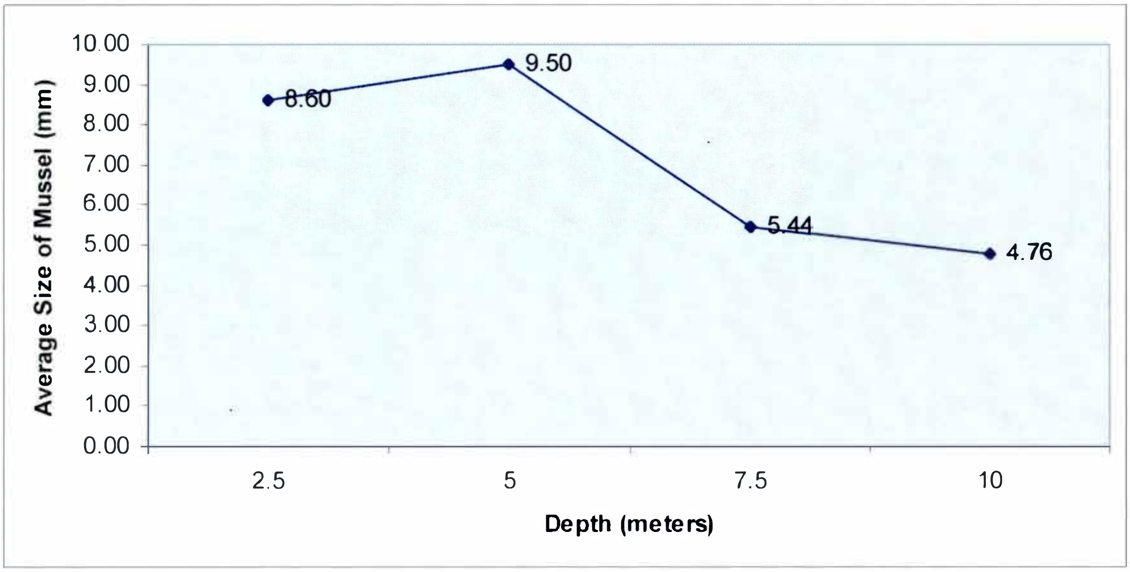

Figure 11: Average size of zebra mussel compared to depth

The average number of zebra mussels at each site varied greatly across the lake. Figure 12 shows the average number of mussels found at each site. Four main sites have high counts of mussels (site 361, 331, 287, and 207). Site 361 contained the most zebra mussels with a count of 610. Sites 331, 287, and 207 followed with a count of 480, 434, and 420 mussels respectively. Since there were a small number of sites, the results of statistical test could not be considered significant. In most cases, the cutoff for the number of sample sites is around 30 for something to be considered statistically significant.

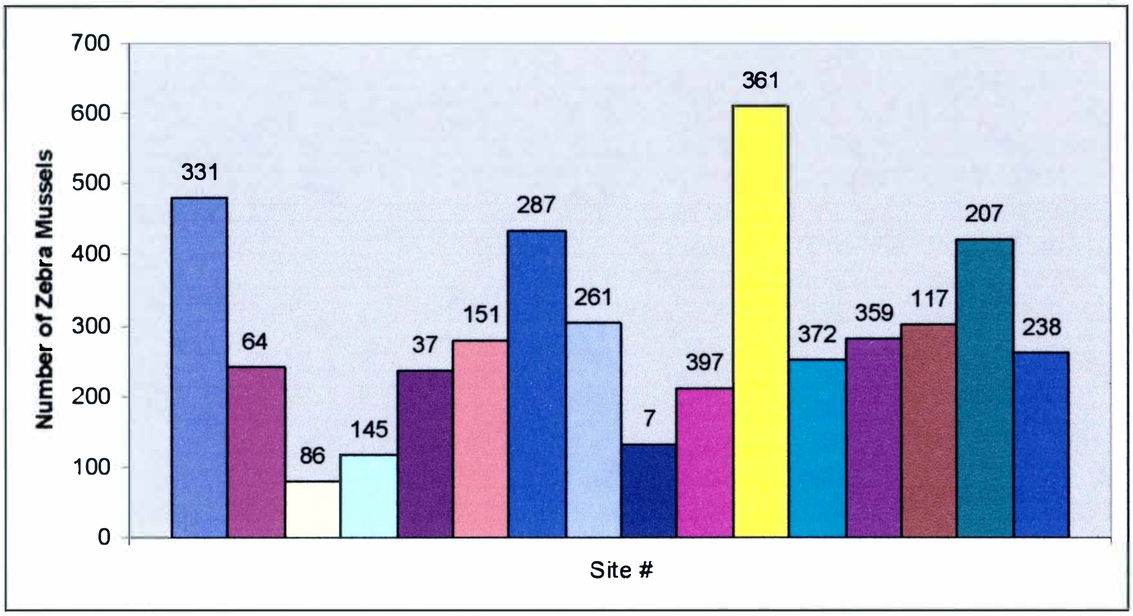

Figure 12: Number of zebra mussels per site

Analysis of Variance

During the analysis, the variables including substrate and vegetation had to be transformed into categorical values because SPSS would not recognize their nominal descriptions. Each of the different types of substrates were assigned a different number. This was done with the vegetation variables as well. The results from the Analysis of Variance test are shown in Tables 7, 9, and 10.

Table 7: Analysis of Variance test with independent variable of depth (4 classes)($\alpha = .10$)

Variable		SS	Df	MS	F	Sig.
Average Number	Between Groups	4978.813	3	1659.604	.127	.944
	Within Groups	782709.125	60	13045.152		
	Total	787687.938	63			
Average Size	Between Groups	259.602	3	86.534	3.298	**.026***
	Within Groups	1574.227	60	26.237		
	Total	1833.829	63			

The Analysis of Variance Test of four groups of depth revealed one significant relationship at a .10 significance level (average size = 0.026). Therefore, the null hypothesis that the average size of zebra mussels does not vary with depth can be rejected. Also, the null hypothesis that the number of mussels does not vary with depth fails to be rejected. To further understand the meaning of this significance, and to see which specific depths have significant relationships, Tukey's Post Hoc test was applied (Table 8). At the 5 and 10 meter depths, there is a significant difference between the means of the average size of zebra mussels.

Table 8: Tukey's Post Hoc test for ANOVA with factor being depth ($\alpha = .10$)

Dependent Variable	(I) depth	(J) depth	Mean Difference (I-J)	Std. Error	Sig.
Average Size	2.5	5.0	-.899938	1.810977	.959
		7.5	3.153625	1.810977	.312
		10.0	3.841625	1.810977	.158
	5.0	2.5	.899938	1.810977	.959
		7.5	4.053563	1.810977	.125
		10.0	**4.741563**	1.810977	**.053***
	7.5	2.5	-3.153625	1.810977	.312
		5.0	-4.053563	1.810977	.125
		10.0	.688000	1.810977	.981
	10.0	2.5	-3.841625	1.810977	.158
		5.0	**-4.741563**	1.810977	**.053***
		7.5	-.688000	1.810977	.981

The Analysis of Variance Test of substratum type revealed that there is not a statistically significant relationship between substratum type, average size, and the average number (count) of zebra mussels at the 90% level (Table 9). Therefore, the null hypothesis that the number and average size of mussels does not vary with substratum type fails to be rejected. In the ANOVA test (Table 10) of vegetation type, there were not any statistically significant relationships between vegetation, average size, and the average number of zebra mussels. The null hypothesis that the number and average size of zebra mussel does not vary with vegetation type fails to be rejected. A better representation of the vegetation types in Gull Lake could merit improved results.

Table 9: Analysis of Variance test with independent variable of substratum type

Variable		SS	df	MS	F	Sig.
Average Number	Between Groups	51933.209	4	12983.302	1.041	.394
	Within Groups	735754.729	59	12470.419		
	Total	787687.938	63			
Average Size	Between Groups	138.813	4	34.703	1.208	.317
	Within Groups	1695.015	59	28.729		
	Total	1833.829	63			

Table 10: Analysis of Variance test with independent variable of vegetation type

Variable		SS	df	MS	F	Sig.
Average Number	Between Groups	28774.168	2	14387.084	1.156	.321
	Within Groups	758913.769	61	12441.209		
	Total	787687.938	63			
Average Size	Between Groups	60.030	2	30.015	1.032	.362
	Within Groups	1773.798	61	29.079		
	Total	1833.829	63			

Chi-Square

A Chi-Square test was performed on three groups including depth, vegetation type, and substrate type, in relation to the average number of zebra mussels (count). The first Chi-Square analysis of the relationship between vegetation and substratum shows the values inside the cells which represent raw counts for zebra mussel abundance throughout Gull Lake. It is noteworthy that submersed vegetation accounted for around 90% of the vegetation type in Gull Lake. The marl and pulpy peat substratum type accounted for the majority of the sediment in Gull Lake (approximately 84%). When looking at the 16 sites throughout the lake, 81% of the locations contain submersed vegetation, while 12.5% contain emergent, and 6.25% contain floating vegetation respectively. Substratum types were represented in a more equal fashion, where 43.75% of the site had fibrous peat and sand, 31.25% contained marl and pulpy peat, 12.5% had pulpy peat, and fibrous peat along with sand and marl both represented 6.25% respectively. Figure 13 shows the relationship between substrate type and the number of zebra mussels. Note that fibrous peat and sand had the highest number of zebra mussel with a count of 1789 mussels. Table 11 shows the observed values for the Chi-Square Analysis for the two variables.

Table 11: Observed values for Chi-Square analysis between substratum and vegetation

	Submersed	Emergent	Floating	Total
Marl and pulpy peat	1079	133	0	1212
Fibrous peat and sand	1486	303	0	1789
Pulpy peat	914	0	0	914
Fibrous peat	0	0	610	610
Sand and marl	117	0	0	117
Total	3596	436	610	**4642**

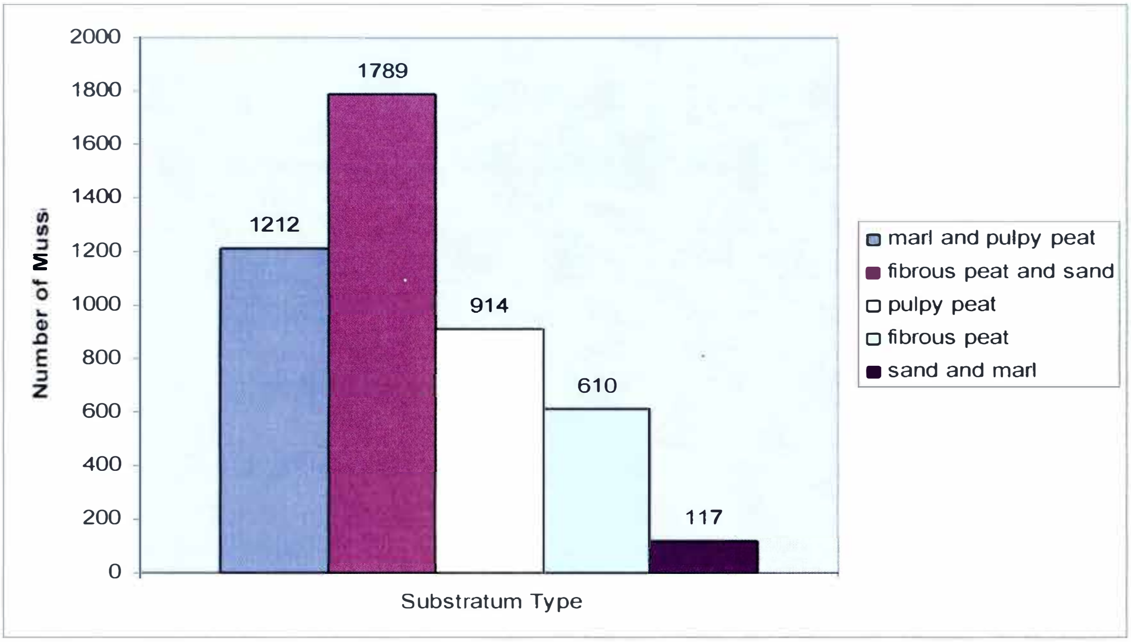

Figure 13: Number of zebra mussels according to substrate type

At first glance of the observed values, it may appear that the zero values would be somewhat cumbersome and limiting in a Chi-Square Analysis. This notion is rectified in that none of the expected values (Table 12) contain values less than 5. These values were calculated by summing the observed values according to category, taking the product of the row and column totals, and dividing the product by the total number of zebra mussels in Gull Lake.

Table 12: Expected values for Chi-Square analysis between substratum and vegetation

	Submergent	Emergent	Floating
Marl and pulpy peat	939	114	159
Fibrous peat and sand	1386	168	235
Pulpy peat	708	86	120
Fibrous peat	473	57	80
Sand and marl	91	11	15

Next, the Chi-Square values (Table 13) were calculated by the using the equation presented in Chapter 3. The expected value is subtracted from the observed value and squared, followed by the division of the expected value. To find the Chi-Square value, these numbers were then summed and subtracted from the total count of zebra mussels in the lake.

Table 13: Chi-Square values from the analysis between substratum and vegetation

	Submergent	Emergent	Floating	Total
Marl and pulpy peat	21	3	159	
Fibrous peat and sand	7	108	235	
Pulpy peat	60	86	120	
Fibrous peat	473	57	3502	
Sand and marl	8	11	15	
Total				**X^2 = 4,866** **CV = 15.507** **α = .05** **df = 8**

Once the Chi-Square value was obtained ($X^2 = 4,866$), the comparison to the critical value (15.507) showed that there indeed was a statistically significant relationship ($\alpha = .05$, df = 8) between vegetation and substratum type in relation to the number of zebra mussels in Gull Lake. Therefore, the null hypothesis that the number of zebra mussels does not vary between substrate and vegetation type is rejected. The results showed that approximately 32% of zebra mussel abundance was correlated with the environmental components of submersed vegetation and fibrous peat and sand sediments. Also, approximately 23% of zebra mussel abundance was accounted for by areas associated with submersed vegetation and fibrous peat and sand sediment.

The results also indicated that 77.5% of the zebra mussel abundance in Gull Lake is accounted for by submersed vegetation. This result is comparable to Karatayev *et al.* (1998) who found that submerged portions of macrophytes were considered suitable substrates for mussels. Also, the two most abundant substratum types (marl and pulpy peat and fibrous peat and sand) account for approximately 65% of zebra mussel proliferation in Gull Lake. The other three sediment types account for 35% of the abundance of zebra mussels. Figure 14 looks at the relationship between vegetation type and the number zebra mussels. Submersed vegetation accounted for 3956 zebra mussels, where emergent and floating vegetation accounted for 1046 mussels.

A second Chi-Square test was completed on the variables of depth and substratum type, and their relationship to the number of zebra mussels in Gull Lake. The significance level was set at $\alpha = .05$ with 12 degrees of freedom. The Chi-Square Distribution Table revealed that the critical number is 21.026. Table 14 shows the observed values for the Chi-Square test between depth and substratum type.

Table 14: Observed values for Chi-Square analysis between depth and substratum

	2.5	5	7.5	10	Total
Marl and pulpy peat	0	516	133	563	1212
Fibrous peat and sand	322	303	463	701	1789
Pulpy peat	480	434	0	0	914
Fibrous peat	0	0	610	0	610
Sand and marl	117	0	0	0	117
Total	919	1253	1206	1264	**4,642**

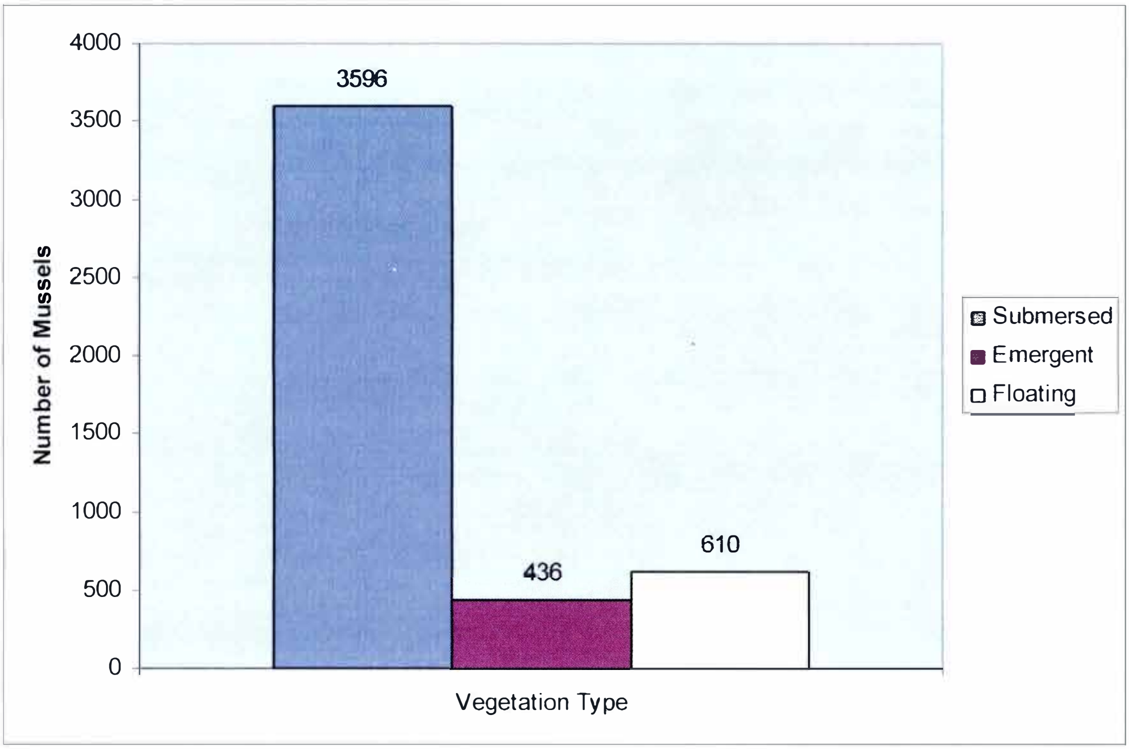

Figure 14: Number of zebra mussels according to vegetation type

Even though the depths were picked randomly at each site throughout the lake, there is an equal distribution of the four sites in the study, where each of the four depths were used 4 times. It is noteworthy that the dominating sediment types are again marl and pulpy peat (84%) and fibrous peat and sand (13.5%) in terms of coverage. Again, with the zero values being present in the observed table, it may seem somewhat limiting to the analysis. Table 15 shows that the expected value are all above 5, which is considered to be the threshold value.

Table 15: Expected values for Chi-Square analysis between depth and substratum

	2.5	5	7.5	10
Marl and pulpy peat	240	327	315	330
Fibrous peat and sand	354	483	465	487
Pulpy peat	181	247	237	249
Fibrous peat	121	165	158	166
Sand and marl	23	32	30	32

The equation from Chapter 3 was used once again to calculate the Chi-Square values (Table 16). The results indicated that there is an undeniable significant relationship between depth and substratum type in relation to the number of zebra mussels in Gull Lake. The Chi-Square Value ($X^2 = 4{,}117$) in comparison to the critical value of 21.026, ($\alpha = .05$, df = 12) reaffirmed this inference. Therefore, the null hypothesis that the number of zebra mussels does not vary between depth and substrate type is rejected.

Table 16: Chi-Square values from the analysis between depth and substratum

	2.5	5	7.5	10	Total
Marl and pulpy peat	240	109	105	164	
Fibrous peat and sand	3	67	0	94	
Pulpy peat	494	142	237	249	
Fibrous peat	121	165	1286	166	
Sand and marl	380	32	30	32	
Total					**$X^2 = 4{,}117$** **CV = 21.026** **$\alpha = .05$** **df = 12**

The results indicated a significant combination of the depth of 10 meters and the sediment type of fibrous peat and sand account for approximately 15% of the zebra mussel abundance at the sample sites. Also, it is noteworthy that the various depths account for a somewhat equal distribution of zebra mussel abundance in the study. This was not consistent with the findings of Mitchell *et al.* (1996) in Lake Erie, where they found that the abundance of zebra mussels increased with depth. The depth of 2.5 meters accounts for about 20% of the number of zebra mussels that were sampled. The depths of 5 and 10 meters accounted for the most abundance, with 26% and 27% respectively. The number of mussels was greatest at the depth of 10 meters (1,264 mussels). The depth of 2.5 meters contained the smallest amount of zebra mussels with a count of 919 mussels. Figure 15 shows the number of zebra mussels according to depth.

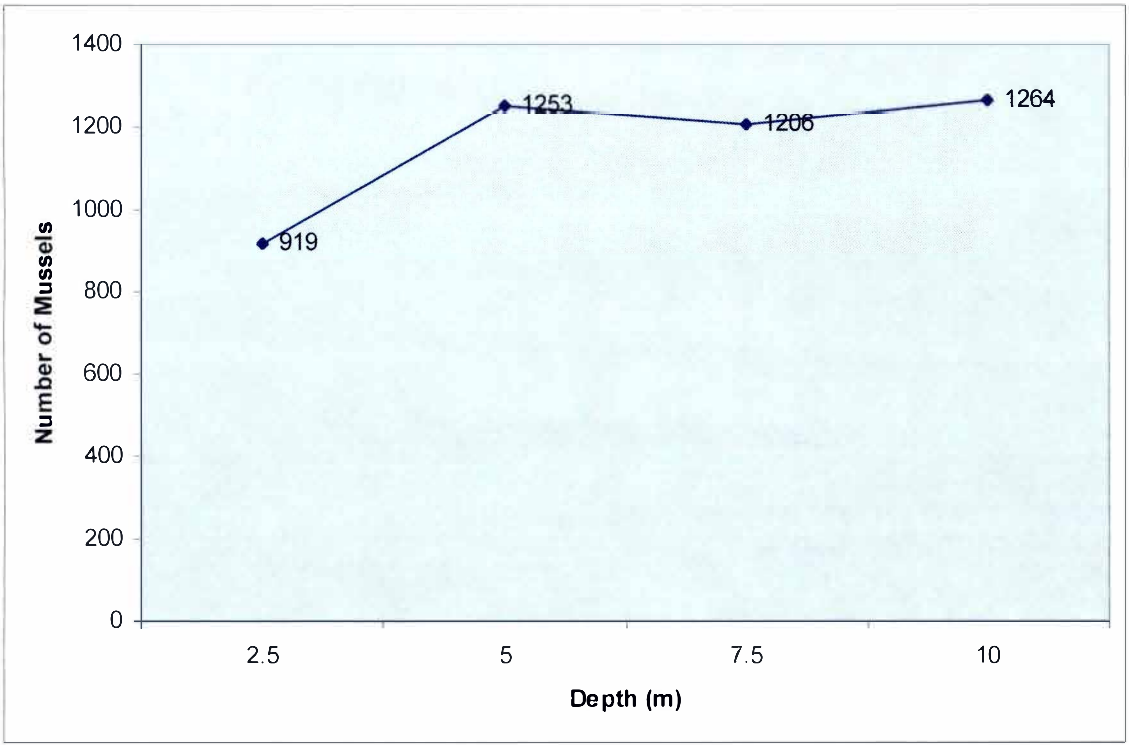

Figure 15: Number of zebra mussels according to depth

A third Chi-Square test was performed to look at the relationship between depth, vegetation type, and the number of zebra mussels. The critical value was determined to be 12.59 ($\alpha = .05$, df = 6). The observed values for the Chi-Square analysis are shown in Table 17. The number of zebra mussels at each vegetation type is located in Figure 14, and the number of mussels at each depth is shown in Figure 15.

Table 17: Observed values for Chi-Square analysis between depth and vegetation type

	Submersed	Emergent	Floating	Total
2.5	919	0	0	919
5	950	303	0	1253
7.5	463	133	610	1206
10	1264	0	0	1264
Total	3596	436	610	**4,642**

Although Table 17 contains several zeros, the expected values (Table 18) rectify that the test is acceptable with not having any values below 5. Again, the equation from Chapter III was used to calculate the Chi-Square values (Table 19).

Table 18: Expected values for Chi-Square analysis between depth and vegetation type

	Submersed	Emergent	Floating
2.5	712	86	121
5.0	971	118	165
7.5	934	113	158
10.0	979	119	166

Table 19: Chi-Square values for the analysis between depth and vegetation type

	Submersed	Emergent	Floating	Total
2.5	60	86	121	
5.0	0	292	165	
7.5	238	3	1286	
10.0	83	119	166	
Total				**X^2 = 2,619** **CV = 12.59** **α = .05** **df = 6**

The results show that Chi-Square exposed a significant relationship between vegetation type and depth in relation to the number of zebra mussels. The X^2 value for the analysis is 2,619, which is much larger than the critical value of 12.59 ($\alpha = .05$, df = 6). Therefore, the null hypothesis that the number of zebra mussels does not vary between depth and vegetation type is rejected.

Overall, the descriptive statistics revealed some variation among the means of the average number and size of zebra mussels at various depths. The means of the average number of zebra mussels vary at a depth of 2.5 m. On average, there are fewer zebra mussels at the depth of 2.5 m than at the other depths. The means of the average number of mussels vary greatly with all of the substrate types as well. This variation may be explained by the inconsistent sample sizes of the substrate types. Also, the means of the average number of mussels vary slightly when floating vegetation is present. The means of the average size of mussel vary greatly among all of the depths in the study. The specific trend seems to be that the average size of the mussels decrease with depth. All of the substrate types showed some variation in the average size of mussels. Finally, the means for the average size of mussels vary among emergent vegetation in Gull Lake.

The analysis of variance tests exposed only one significant relationship. The average size of zebra mussels ($P = 0.026$, $\alpha = .10$) was significant. Tukey's Post Hoc Test revealed that at the 5 and 10 meter depths, there is a significant difference between the means of the average size of zebra mussels. Further ANOVA tests did not reveal any significant relationships between the average number and size of zebra mussels in relation to substrate and vegetation types.

The Chi-Square tests indicate that there is a statistically significant relationship ($X^2 = 4{,}866$, $CV = 15.507$, $\alpha = .05$, $df = 8$) between vegetation and substratum type in relation to the number of zebra mussels. The tests also uncovered a significant relationship ($X^2 = 4{,}117$, $CV = 21.026$, $\alpha = .05$, $df = 12$) between depth and substrate type in relation to the number of zebra mussels. Finally, the results show that there is a highly statistically significant relationship ($X^2 = 2{,}619$, $CV = 12.59$, $\alpha = .05$, $df = 6$) between vegetation type and depth in relation to number of zebra mussels in Gull Lake.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purpose of this research was to assess the relationship between different zebra mussel measurements, bathymetry, substrate, and vegetation types on Gull Lake in Southwestern Lower Michigan. *Dreissena polymorpha* data include 16 sites on Gull Lake, collected in July of 1999 by the Kellogg Biological Station of Michigan State University. GIS was used to process and analyze the data layers to test for correlation between them and the different zebra mussel measurements. A Thiessen polygon was created using the vegetation point data. This proximity function converted the original point data into multiple polygons for analysis. The GIS analysis results showed that the most abundant substrate types were marl and pulpy peat (55.76%) and fibrous peat and sand (24.12%). Submersed vegetation (90.02%) was also found to be the most abundant vegetation type in Gull Lake.

Different statistical tests were performed to test the relationship between depth, substrate, and vegetation type in relation to the average number and size of zebra mussels. The results of an analysis of variance (ANOVA) indicate that the average size of zebra mussel is decreasing with depth ($P = .026$, $\alpha = .10$) between the depths of 5 and 10 meters. The analysis revealed that the overall trend was that the average size (shell length in mm) of the mussels decreased with increasing depth. A Chi-Square analysis was also implemented to test for a significant relationship between the number of zebra mussels, depth, substrate, and vegetation type. The results indicated that there is a significant relationship between depth, substrate type, and the number of zebra mussels ($X^2 = 4,117$, CV = 21.026, $\alpha = .05$, df = 12). Significant relationships also existed between substratum type, vegetation type, and the number of zebra mussels ($X^2 = 4,866$, CV = 15.507, $\alpha = .05$, df = 8), as well as between depth, vegetation type, and the number of zebra mussels ($X^2 = 2,619$, CV = 12.59, $\alpha = .05$, df = 6).

The analysis of variance test and Chi-Square analysis yielded somewhat diverse findings. The ANOVA showed that the average size of mussels were significant at 5 and 10 meter depth, while the Chi-Square analysis showed that the relationships between depth, substrate type, vegetation type, and the number of zebra mussels were significant at the 95% level ($\alpha = .05$). The two statistical tests used dissimilar sets of data, so their results cannot be considered to be similar.

Limitation of Study

There were several limitations of the study that are notable. The main limitation concerned the small number of sample sites (N = 16). The zebra mussel data used for this research was secondary in nature. To compensate for the small sample size, four size classes were created for each of the 16 sites. Mussels from 0 to 30 mm were grouped into the four size classes. This allowed the results of statistical testing to be considered significant.

Another limitation of the study was the limited variation of substratum and vegetation types located in the individual study sites. Only five of the nine substrate types of the lake were present at the study sites. This restricted the range of the analyses and the comparison to other research completed on the relationship between substrate type and zebra mussel abundance. With submersed vegetation being approximately 90% of the total vegetation in Gull Lake, there also was limited variation in vegetation types present at the sites. Musko and Bako (2005) concluded that the types of submerged macrophytes have significant additive and interactive effects on the length of zebra mussels. A future study could look at the different species of vegetation in Gull Lake.

With an area of approximately 2,030 acres, Gull Lake is considered to be the largest inland lake in Kalamazoo County. This particular study only analyzed a limited number of sites based on a zebra mussel inventory of Gull Lake finding a total of 4,642 zebra mussels. Therefore, the mussels have an average density of about 161 mussels per m^2 in the sample region. This will vary greatly throughout the lake. This research was also limited to the littoral region of Gull Lake between the depths of 2.5 and 10 meters. With the sample sites only covering .9 m^2 at each site, a large portion of the lake was left unsampled.

Future Studies

A number of studies can be conducted in the future to improve the understanding of the zebra mussel infestation in Gull Lake. A study with the similar sampling methods to cover more sample sites would be beneficial in getting a broader view of the abundance of zebra mussels. Although the methods are tedious, and the summer months are limited, an extended study would be very valuable. This would allow more statistical tests to be used in the analysis of the data. Also, with a similar study, there could be a larger temporal scale used in the analysis. The data from 1999 could be compared to more recent findings.

Another possible study on Gull Lake could include the sublittoral region of the lake. As stated earlier, this particular study only covered the littoral region from 2.5 to 10 m. A study of the sublittoral region would be advantageous in comparing the abundance and size of zebra mussels at greater depths. Although vegetation would be sparse, different sediment types could be explored as well. This would also allow for the results to be compared to studies done on other lakes that focused on the sublittoral region.

A study that covers a broader range of substrate and vegetation types would be advantageous as well. This study was limited to only five of the nine substrate types. Although substrate type was not found to be a significant contributor to the average number and size of zebra mussels in Gull Lake, it has been acknowledged to be a significant contributor in many other studies. Suitable substrate has been identified as a major factor in the settlement of zebra mussels. It has been observed in other lakes that if a suitable substrate is not present, then the mussels will adapt. Haltuch and Berkaman (2000) found that accumulations of live and dead mussel shells provide a positive feedback where additional mussels may have colonized the biologically generated hard substrates, creating a dynamic benthic habitat. This means that they are essentially transforming soft substrates into hard substrates. A further study of the relationship between sediment type and zebra mussel abundance in Gull Lake would be very valuable to show if this is indeed happening here in Michigan.

Management Suggestions

Zebra mussel proliferation in the United States will increasingly become a larger problem. Laws have been passed to try to help control the spread of invasive species.

Boaters must exercise caution when transporting their vessels from lake to lake. The proper inspections must be made of their trailered boats when taken from the water. New laws have also been passed to ensure that ballast water from ocean freighters do not introduce any new indigenous species.

Although this research only provides a microcosmus of the vast area of Gull Lake's zebra mussel population, its findings may be applicable in other inland lakes as well. Certain physical factors are important in determining the abundance and distribution of zebra mussels in aquatic systems. The analysis of these factors in other lakes may provide generalizations and some differences in the behavior of the mussels. This research has shown that there is a significant relationship between depth and the size of zebra mussels in Gull Lake. These findings may be helpful in explaining and comparing the relationships in other lakes. Although the zebra mussel population cannot be eradicated completely, research has shown and will continue to show that there are methods to control the broadening of this aquatic pest.

BIBLIOGRAPHY

Alfaro, Andrea C. and Jeffs, Andrew G. 2003. Variability in mussel settlement on suspended ropes placed at Ahipara Bay, Northland, New Zealand. *Aquaculture* 216: 115-126.

Bially, Andrew and Macisaac, Hugh J. 2000. Fouling mussels (*Dresissena spp.)* colonize softsediments in Lake Erie and facilitate benthic invertebrates. *Freshwater Biology* 43: 85-97.

Bossenbroek, Jonathan M., Kraft, Clifford E., and Nekola, Jeffrey C. 2001. Prediction of Long-Distant Dispersal Using Gravity Models: Zebra Mussel Invasion of Inland Lakes. *Ecological Applications* 11(6): 1778-1788.

Chakraborti, Rajat K., Kaur, Jagjit, and DePinto, Joseph V. 2002. Analysis of Factors Affecting Zebra Mussels (Dreissena Polymorpha) Growth in Saginaw Bay: A GIS-Based Modeling Approach. *Journal of Great Lakes Research* 28(3): 396-410.

Coakley, John P., Brown, Glenn R., Ioannou, Stefan E., and Charlton, Murray N. 1997. Colonization Patterns and Densities of Zebra Mussels (*Dreissena*) in Muddy Offshore Sediments of Western Lake Erie, Canada. *Water, Air and Soil pollution* 99: 623-632.

Conner-Linton, Jeff. 2003. Chi-Squared Tutorial. [On-line]. Available at http://www. georgetown.edu/faculty/ballc/webtools/web_chi_tut.html.

Dermott, R. and Manawar M. 1993. Invasion of Lake Erie;s Offshore Sediments by *Dreissena*, And it's Ecological Implication. *Canadian Journal of Fisheries and Aquatic Science* 50: 2298-2304.

Dexter, James L. Jr. 1996. Gull Lake. *Michigan Department of Natural Resources Status of Fishery Resource Report* 96-97.

Downing, Jill. 2003. Hyperspectral Remote Sensing of Gull Lake Water Quality, Summer of 1998. Master's thesis, Western Michigan University.

Fleischer, Guy W., DeSorcie, Timothy J., and Holuszko, Jeffrey D. 2001. Lake-wide Distribution of *Dreissena* in Lake Michigan, 1999. *Journal of Great Lakes Research* 27(2): 252-257.

Fotheringham, Stewart A., Brunsdon, Chris, and Charlton, Martin. 2000. *Quantitative Geography: Perspectives on Spatial Data Analysis.* London, England: Sage Publications Ltd.

Griffiths, Ronald W., Schloesser, Donald W., Leach, Joseph H., and Kovalak, William P. 1991. Distribution and Dispersal of the Zebra Mussel (*Dreissena Polymorpha)* in the Great Lakes Region. *Canadian Journal of Fisheries and Aquatic Science* 48: 1381-1388.

Haltuch, Melissa A., Berkman, Paul A., and Garton, David W. 2000. Geographic information Systems (GIS) analysis of ecosystems invasion: Exotic mussels in Lake Erie. *Limnology and Oceanography* 45(8): 1778-1787.

Herbert, P. D. N., Muncaster, B. W., and Mackie, G. L. 1989. Ecological and genetic studies on Dreissena polymorpha (Pallas): a new mollusk in the Great Lakes. *Canadian Journal of Fisheries and Aquatic Science* 46: 1587-1591.

Horvath, Thomas G., Martin, Kristine M., and Lamberti, Gary A. 1999. Effect of Zebra Mussels, Dreissena Polymorpha, on Macroinvertebrates in a Lake-outlet Stream. *The American Midland Naturalist* 142 (2): 340.

Jackson, Julia A. 1997. *Glossary of Geology, Fourth Edition.* Alexandria, Virginia: American Geological Institute.

Karatayev, Alexandra Y., Burlakova, Lyubov, E., and Padilla, Dianna K. 1998. Physical Factors That Limit the Distribution and Abundance of *Dreissena polymorpha. Journal Of Shellfish Research* 17(4): 1219-1235.

Koutnik, Michael, A. and Padilla, Dianna K. 1994. Predicting the Spatial Distribution of *Dreissena Polymorpha* (Zebra Mussel) among Inland Lakes of Wisconsin: Modeling with a GIS. *Canadian Journal of Fisheries and Aquatic Science* 51: 1189-1196.

Kraft, Clifford E. and Johnson, Ladd E. 2000. Regional differences in rates and patterns of North American inland lake invasions by zebra mussels (Dreissena polymorpha). Canadian Journal of Fisheries and Aquatic Sciences 57: 993-1001.

Lane, David M. 2000. HyperStat Online. [On-line] Available: http://davidmlane.com/ hyperstat/index.html.

Leung, Brian, Drake, John M., and Lodge, Davis, M. 2004. Predicting Invasions: Propagule Pressure and the Gravity of Allee effects. *Ecology* 85(6): 1651-1660.

Mantecca, Paride, Vailati, Giovanni, Garibaldi, Letizia, and Bacchetta, Renato. 2003. Depth Effects on Zebra Mussel Reproduction. *Malacologia* 45(1):109-120.

Marsch, Jonathan P. 2003. Shoreline Perceptions and Planning for Five Lakes in Kalamazoo County, Michigan. Master's Thesis, Western Michigan University.

Mellina, Eric and Rasmussen, Joseph B. 1994. Patterns in the Distribution and Abundance of Zebra Mussel (*Dreissena polymorpha*) in Rivers and Lakes in Relation to Substrate and Other Physiochemical Factors. *Canadian Journal of Fisheries and Aquatic Science* 51: 1024-1036.

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

Mills, E.L., Chrisman, Jana R., Baldwin, Brad, Owens, Randall W., Gorman, Robert O., Howell, Todd, Roseman, Edward F., and Raths, Melinda K. 1999. Changes in the Dreissenid Community in the Lower Great Lakes with Emphasis on Southern Lake Ontario. *Journal of Great Lakes Research* 25(1): 187-197.

Mitchell, Jeremy S., Baily, Robert C., and Knapton, Richard W. 1996. Abundance of *Dreissena Polymorpha* and *Dreissena bugensis* in a warmwater plume: effects of depth and Temperature. *Canadian Journal of Fisheries and Aquatic Science* 53: 1705-1712.

Moss, B. 1972. Studies on Gull Lake Michigan I. Seasonal and depth distribution of Phytoplankton. *Freshwater Biology* 2: 289-307.

Musko, Ilona B. and Bako, Beata. 2005. The density and biomass of *Dreissena polymorpha* Living on Submersed macrophytes in Lake Balaton (Hungary). *Arch. Hydrobiologia* 162(2): 229-251.

Neng, Yu and Culver, David A. 1999. *In situ* survival and growth of zebra mussels (*Dreissena Polymorpha*) under chronic hypoxia in a stratified lake. *Hydrobiologia* 392: 205-215.

Padilla, Dianna K., Chotkowski, M.A., Buchan, A.J. 1996. Predicting the spread of zebra mussels (*Dresissena polymorpha*) to inland waters using boater movement patterns. *Global Ecology and Biogeography Letters* 5: 353-359.

Raikow, David F., Sarnelle, Orlando, Wilson, Alan E., and Hamilton, Stephen K. 2004. Dominance of the noxious cyanobacterium *Microcystis aeruginosa* in low-nutrient lakes is associated with exotic zebra mussels. *Limnology and Oceanography* 49(2): 482-487.

Rogernson, Peter, A. 2001. *Statistical Methods for Geography.* London, England: Sage Publications Ltd.

Sarnelle, Orlando. 1999. Zebra mussel sampling on Gull Lake. Kellogg Biological Station, Michigan State University.

Skubinna, John P., Coon, Thomas G., and Batterson, Ted R. 1995. Increased Abundance and Depth of Submersed Macrophytes in Response to Decreased Turbidity in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* 21(4): 476-488.

Szabo Craft, Lidia. 1952. Digital Water Atlas. Michigan Department of Natural Resources. Ann Arbor, Michigan.

Taube, C.M. and Bacon, E.H. 1952. Lake inventory summary – no.2 Gull Lake. Institute for Fisheries Research, Michigan Department of Conservation, Cooperating with the University of Michigan.

Tessier, A. 2001. The Gull Lake Story. Report submitted to the Gull Lake Quality Organization, Inc. by the Kellogg Biological Station. [On-line]. Available: http://mlswa.org/glqo-321/history_kbs.html.

Toczylowski, Susan A., Hunter, Douglas R., and Armes, Lisa M. 1999. The Role of substratum Stability in Determining Zebra Mussel Load on Unionids. *Malacologia* 41(1):151-162.

Wilson, Alan E. and Sarnelle, Orlando. 2002. Relationship between zebra mussel biomass and Total phosphorus in European and North American lakes. *Arch. Hydrobiologia* 153(2): 339-351.