ANALYSIS OF WATER CLARITY, DISSOLVED OXYGEN, TOTAL AMMONIA, TOTAL PHOSPHORUS, AND CHLOROPHYLL *a* OF OOLOGAH LAKE, OKLAHOMA, AFTER ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) INVASION

By

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ANALYSIS OF WATER CLARITY, DISSOLVED OXYGEN, TOTAL AMMONIA, TOTAL PHOSPHORUS, AND CHLOROPHYLL *a* OF OOLOGAH LAKE, OKLAHOMA, AFTER ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) INVASION

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CHAPTER I

INTRODUCTION

Since the their introduction into the Great Lakes system in 1986, zebra mussels (*Dreissena polymorpha*) have made their way to the interior water bodies of Oklahoma via navigable waterways and overland transport (Ludyanskiy *et al.*, 1993; Johnson *et al.*, 2001). Zebra mussels were first discovered and documented in Oologah Lake in 2003 (Boeckman and Bidwell, 2010). Oologah Lake has been sampled for water quality purposes on a monthly basis from January 2000 through to December 2008 (except only the latter months of 2002) at the same stations by the U.S. Army Corps of Engineers, Tulsa District personnel. For this reason, Oologah Lake is an optimal system to study water quality parameters pre- and post-zebra mussel invasion. During the course of zebra mussel presence and height of their population density within the lake, a significant population die-off was recorded in June 2006, when the density count went from 150,000 individuals/m^2 to less than 4,500 individuals/m^2 (Boeckman and Bidwell, 2008).

Being highly efficient filter feeders (USACE, 1993), a high enough zebra mussel population density has the capability to filter the water column of their system. Secchi depth, dissolved oxygen, total ammonia, total phosphorus, and chlorophyll *a* have been studied in other lake and river systems in the northern states in United States; all of the parameters listed were reported to be impacted by zebra mussels (Caraco *et al.*, 2000; Holland, 1993; Holland *et al.*, 1995; Effler *et al.*, 1996, Effler *et al.*, 2004; Higgins and Vander Zanden, 2010; Johengen *et al.*, 1995; Mellina *et al.*, 1995; Yu and Culver, 2000). In this study, analysis of the same water quality parameters are analyzed to determine if Oologah Lake, a man-made reservoir with controlled flow releases for navigation and flood control (USACE, 2004), exhibits the same response to the zebra mussel impacts reported in the previous studies.

CHAPTER II

REVIEW OF LITERATURE

Background of Zebra Mussels

To understand all of the impacts that zebra mussels, *Dreissena polymorpha*, can have on an ecosystem, it is important to discuss their life history. Zebra mussels are native to the Caspian, Aral, Azov, and Black Seas in Eastern Europe (Ludyanskiy *et al.*, 1993). They are a small bivalve, growing to the size of a thumbnail, but can reach up to 30-35 mm in length. They are proficient filter feeders; adults are estimated to filter up to 1 liter of water per day (USACE, 1993). Zebra mussels form dense colonies that can reach densities up to 700,000 individuals/m^2 (USGS, 2010). The zebra mussels' lifespan is anywhere from three to five years with sexual maturity reported to be reached during their first year in United States waters (Ludyanskiy *et al.*, 1993). During spawning season, female adults can release up to one million eggs which are fertilized externally (USGS, 2010); the mussel's reproductive capabilities have facilitated the spread and establishment of dense populations in a short amount of time (Ram *et al.*, 1996). The larvae form of zebra mussels, called veligers, are microscopic and free floating, which makes them easily transportable in the live wells of boats, in ballast water of ships, in bilge pumps, and in between the fibers of a rope attached to anchors. The adults have strong byssal threads that allow for secure attachment on virtually any hard surface, which includes other (native) bivalves. Attached adults can live out of water for up to 30 days in dark, moist conditions (Zook, 2010). These characteristics make an aggressive, top-competitor that is able to establish and disperse quickly when introduced into a new ecosystem.

When the zebra mussels arrived in Lake St. Clair, a small lake within the Great Lakes System between Lake Huron and Lake Erie, in 1986 from the ballast water of a cargo ship from Europe, they were able to settle and subsequently establish a dense population in a short period of time. By 1990, the zebra mussels had established populations throughout the Great Lakes (USGS, 2010). The mussel's high densities and clustering habit led to immediate economic problems; the mussels clogged intake pipes for various industrial facilities that used lake water and the mussels also caused problems for the commercial and recreational boater. Pimentel *et al*. (2000) reported that zebra mussels alone will cause an estimated $100 million in damages and control costs in the United States annually.

Along with economic harm caused by the zebra mussel, the invasive mussel's filtering efficiency led to biological harm to the native aquatic biota in North America. Zebra mussels impact the native biota indirectly by reducing the available food source within the system through their efficient filtering ability and directly by being able to physically attach to their competitors. The most notable impacts have been on native bivalve populations in the system that they invade. Strayer and Malcom (2007) studied the native bivalve population dynamics and found that several native species showed a short term decline after the zebra mussels invaded the Hudson River in 1991. However, some populations rebounded 10 years post invasion (Strayer and Malcom, 2007). Along with the decline in population size, native bivalves sampled also exhibited decline in growth and body condition immediately after the arrival of the invading mussels (Strayer and Malcom, 2007).

Dispersal and Distribution in the United States

Zebra mussels are noted to have arrived in the Laurentian Great Lakes in 1986 (Holland *et al.*, 1995; Arnott and Vanni, 1996; Mackie and Schloesser, 1996); however, they are noted to have arrived in Lake St. Clair in 1988 (Aldridge *et al.*, 1995; MacIsaac *et al.*, 1992). Zebra mussel distribution throughout the northeastern United States was widespread and rapid upon arrival, with populations well established by 1990 (Bossenbroek *et al*., 2007). The mussels have natural and human-related dispersal pathways (Mackie and Schloesser, 1996), and they can be dispersed easily in each stage (larval, juvenile, and adult) of their life cycle (Ludyanskiy *et al.*, 1993); Johnson *et al.*, (2001) reported overland recreational boating activities transport all stages of zebra mussels via live wells, bilges, bait buckets, and most commonly on entangled macrophytes attached to trailers and sometimes anchors. The rapid expansion of the zebra mussels in the northeastern states upon arrival was probably due to the connectivity of water bodies via the navigation channels (Bossenbroek *et al*., 2007). Zebra mussels have also invaded western states via both natural and human related pathways. However, Effler *et al*. (1996) reported uncertainty as to the mussel's success in water bodies that experience increased water temperatures during the summer months. Although the dispersal of the mussels to the more western states has occurred, it has occurred at a much slower rate than in the northeastern states (Bossenbroek *et al*., 2007). Even at the slower rate described by Bossenbroek *et al*. (2007), the establishments of zebra mussels in the western states' reservoirs provide higher invasion rates than a natural, disconnected lake (Havel *et al*., 2005). Downstream transport provided by riverine systems and reservoirs enhances immigration of the free floating veligers and their subsequent colonization, while overland transport to the more isolated inland waters is mainly dependent upon recreational fishing boats, which results in a slower invasion rate (Havel *et al*., 2005).

Even in their native region, zebra mussels have not been able to colonize all waters successfully (Ludyanskiy *et al.,* 1993). Being able to determine the zebra mussels' limitations and tolerances upon introduction into a new ecosystem is a tool many researchers have used to predict which U.S. waters are at higher risk of successful invasion (Ludyanskiy *et al.,* 1993). The primary environmental requirements for zebra mussels are mainly temperature and water quality; secondary requirements include substrate types, hydrology of the system, and existence of structures like dams (Ludyanskiy *et al.,* 1993). The known primary habitat requirements of the mussel, more specifically the water chemistry tolerances of the zebra mussels are: pH > 7.3, calcium concentrations > 20 mg/l, dissolved oxygen concentrations between 8 – 10 mg/l, and an average summer water temperature between 17°C and 23°C (Effler *et al*., 1996). Researchers are now discovering that the invasive species are more tolerant of warm water temperatures and are therefore able to expand their range to the southern states (Ludyanskiy *et al.,* 1993; Nichols, 1996; Hosking *et al*., 1997). Elderkin (2005) tested the temperature tolerances among three separate populations of zebra mussels along the Mississippi River and discovered that the Baton Rouge, Louisiana population adapted to the increased water temperatures; this population showed significantly longer mean time to death with temperatures up to 32°C. Currently, zebra mussels have established and continue to have thriving populations as far south as Texas, Alabama, and Louisiana.

Water Quality Impacts

Research has shown that zebra mussels can have an impact on the aquatic ecosystem they invade by affecting the water quality. However, this ecological impact is not as immediately evident or detectible as are the economic impacts. The water quality parameters found to be the most affected by zebra mussels are the water clarity, dissolved oxygen levels, ammonia concentrations, total phosphorus concentrations, and chlorophyll *a* concentrations (Holland *et al*., 1995; Effler *et al*., 1996; Yu and Culver, 2000; Effler *et al*., 2004). Zebra mussel invasion was not anticipated prior to their arrival; therefore, planning ahead and gathering consistent water quality data of each system in anticipation for a comparison analysis of before and after zebra mussel arrival has not been done. Fortunately, some lakes have enough pre zebra mussel invasion water quality data for other reasons that allow for comparative analysis.

Water Clarity

The turbidity of a reservoir is the accumulation of suspended particles that include phytoplankton, zooplankton, and other organic and inorganic matter (Wetzel and Likens, 2000). The trophic state of a reservoir can be partially described by how much suspended particulate matter is in the water column by measuring with a Secchi Disk. A reservoir has particulate loadings from the various tributaries that flow into the system, and it also has autochthonous nutrient cycling. Zebra mussels have been found to increase Secchi depth (Holland, 1993; Johengen *et al*., 1995; Effler *et al*., 1996; Effler *et al*., 2004). Effler *et al*. (2004) reported that the median Secchi Disk depth increased 2.5 fold from the median Secchi Disk depth measurements recorded before the zebra mussels arrived. An increase of this proportion can have an impact on the depth to which light can pass through, which could impact epilimnion temperature and depth, dissolved oxygen levels, as well as aquatic plant communities.

Dissolved Oxygen

In aquatic systems, the chemical reactions involved in nutrient cycling depend on the oxygen structure (Yu and Culver, 2000). Dissolved oxygen and temperature are inversely related (Horne and Goldman, 1994). Long term changes in the dissolved oxygen concentration levels in a reservoir lead to drastic changes in the productivity of the system (Wetzel, 1983).

Zebra mussels can have both an indirect and a direct affect on the dissolved oxygen concentrations in a reservoir. Indirect changes come from the water clarity that the filtering mussel increases (Yu and Culver, 2000). Direct changes stem from the mussel's oxygen consumption rate. In association with water clarity increasing in a reservoir, the dissolved oxygen profile can often change due to the light being able to penetrate deeper into the water column. By doing this, the epilimnion of a stratified lake can become deeper, therefore changing the thermal structure of the stratification layers

(Yu and Culver, 2000). The dissolved oxygen concentration levels subsequently respond to these changes by decreasing with the increased temperatures of the water column (Yu and Culver, 2000). A lake system with an established population of zebra mussels will naturally have higher oxygen consumption levels. However, this is becoming even more evident in the southern states where average summer water temperatures are higher. Aldridge *et al.* (1995) reported that zebra mussels that were acclimated to higher temperatures had an increased rate of oxygen consumption, putting more pressure on the system.

Total Ammonia

There are various forms of nitrogen in lakes. Separate measurements for nitrate, nitrite, and ammonia concentrations can be made and all of the forms play a specific role in the nitrogen nutrient cycling of a lake (Horne and Goldman, 1994). In nitrogen cycling of a lake, oxygen is very important; the cycle of nitrogen to and from its various usable forms is dependent on the oxygen concentration levels in the lake (Horne and Goldman, 1994).

Since nitrogen is often the limiting nutrient in an aquatic ecosystem (Horne and Goldman, 1994), it is important to discuss the impacts that zebra mussels have on this essential nutrient. Nitrogen concentrations can be impacted by both the filtering efficiency of zebra mussels and as the excretory product of the mussel. Ammonia is the major excretory product of aquatic organisms and is important to monitor in aquatic systems because of its high toxicity at elevated pH levels (Horne and Goldman, 1994).

When a system is faced with an invasion of organisms with such efficient filtering capabilities and rapid reproductive rates, enabling them to reach high densities in a relatively short period of time, noticeable differences in nutrient concentrations after their establishment would be expected. In previous studies, ammonia concentrations were found to have increased after zebra mussel invasion and establishment (Holland *et al*., 1995; Effler *et al*., 2004). While the increase in ammonia concentrations in some systems has been attributed to zebra mussel excretion, the increased concentration in ammonia can also be contributed indirectly by the reduced demands for the nutrient from the zebra mussel feeding on the phytoplankton biomass (Effler *et al*., 1996). As an added note, the nitrogen and phosphorus that the zebra mussels cycle back into the system by excretion may ultimately shift algal species dominance in that system (Arnott and Vanni, 1996).

Total Phosphorus

For many lakes, phosphorus is present in such low concentrations that it becomes the growth-limiting nutrient (Horne and Goldman, 1994). Unlike nitrogen, phosphorus is retained in the soils and root zones of plants within a watershed (Horne and Goldman, 1994). Because of this, not a lot of external loading into a system occurs except in areas of agriculture or industrial waste water discharge sites; however, the increased phosphorus concentration from this type of loading was shown to remain localized and not spread throughout system (Holland *et al.*, 1995). Algal growth has been shown to depend on the amount of phosphorus in the system as well (Wetzel, 1983). This is of particular importance because some algal species produce harmful toxins that are released back into the system.

In previous studies, zebra mussels have been shown to impact phosphorus concentrations in the water column by filtering and by excretion (Mellina *et al.*, 1995; James *et al.*, 2001). However, Effler *et al.* (2004) showed that between nitrogen and phosphorus, zebra mussels had the least impact on mean total phosphorus concentrations. Holland *et al*. (1995) also reports that zebra mussel invasion has had little impact on total phosphorus concentration in Hatchery Bay area of Lake Erie.

Chlorophyll *a*

Being the primary photosynthetic pigment, chlorophyll *a* concentration can be measured to describe the phytoplankton community in a lake (Wetzel, 1983; Wetzel and Likens, 2000). In a phosphorus limiting system, phosphorus and chlorophyll *a* have a direct linear relationship: the greater the total phosphorus concentration, the more chlorophyll *a* can be expected in the system.

Zebra mussels are known to increase water clarity, either directly by filtering (also known as grazing pressure) or indirectly by affecting the availability of nutrients to phytoplankton communities in the system. Mellina *et al.* (1995) indicated that zebra mussels affected algal levels directly by filtering the phytoplankton and not by nutrient depletion. The research by Effler *et al.* (2004) reported that there was a significant decrease in chlorophyll *a* since zebra mussel invasion, with little impact on total phosphorus concentration. Both studies describe that zebra mussels affect algal levels directly by filtering the phytoplankton and not by nutrient depletion, decoupling the phosphorus and chlorophyll *a* relationship.

CHAPTER III

METHODOLOGY

Description of Study Area

Oologah Lake is located in northeastern Oklahoma along the Verdigris River in Rogers and Nowata Counties (Figure 1). Oologah Dam, an U.S. Army Corps of Engineers' project, is located at river mile 90.2 (USACE, 2004). The authorized project purposes for Oologah Lake consist of flood control, water supply, navigation, as well as for recreation and fish and wildlife uses (USACE, 2004). The volume of the lake at the top of the conservation pool (elevation of 638 feet) is 552,235 acre-feet, with a surface area of 31,043 acres. This includes 342,600 acre-feet (154 mgd) of water for water supply purposes and 168,000 acres-feet for navigation purposes (USACE, 2004).

The Oologah Lake watershed consists of 4,247 mi^2 of land; the majority of the watershed is in Kansas and only 19% in Oklahoma (USACE, 2002). The major land uses within the watershed are as follows: 40% unmanaged grasslands, 30% managed pasture land, 11% croplands, 8% forest, and 11% of the watershed land has other minor land uses (i.e. residential, roads, wetlands, and open water) (USACE, 2002).

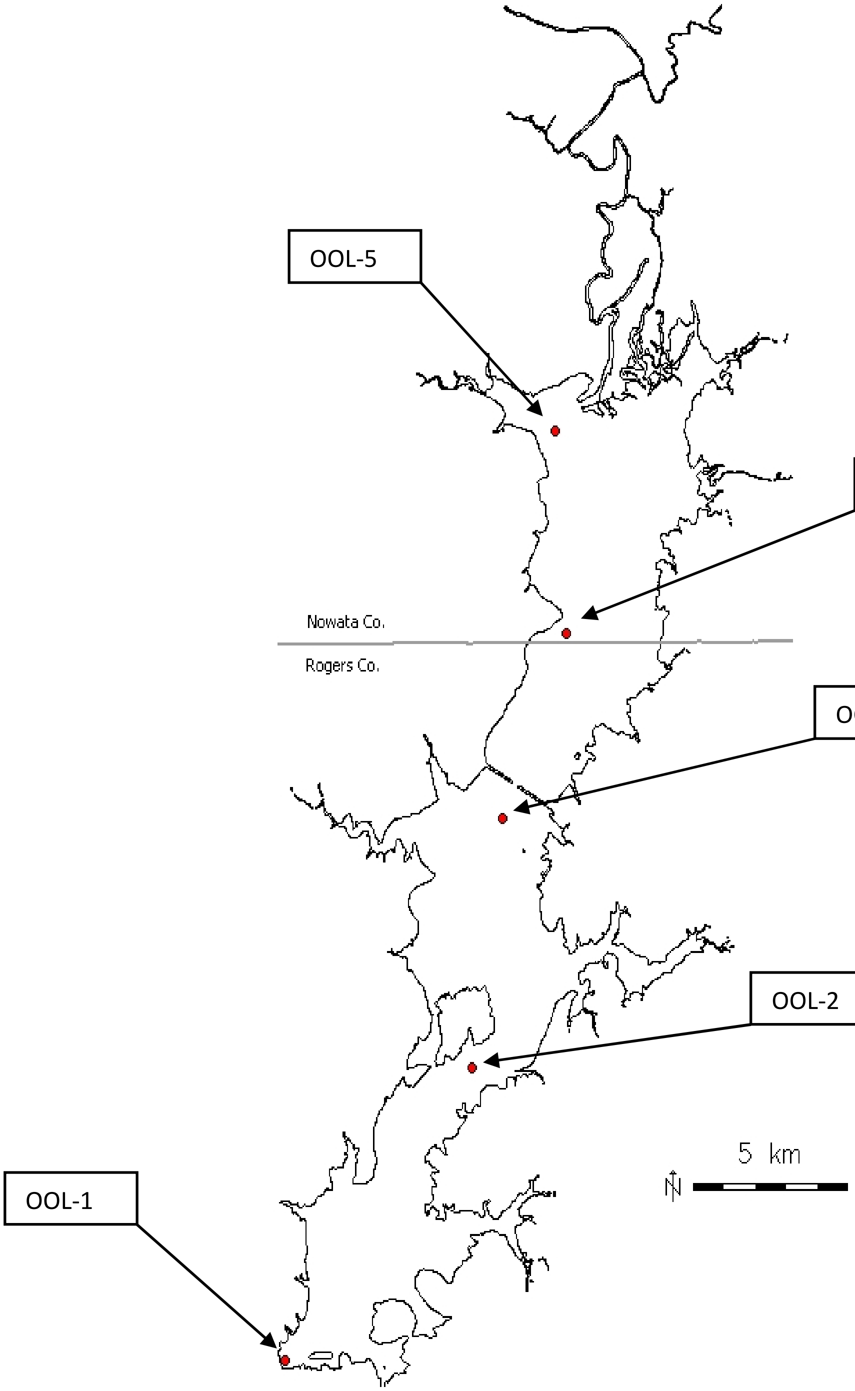

Figure 1. Oologah Lake with sampling station locations and County delineation. Source: David Gade, Limnologist, US Army Corps of Engineers, Tulsa District 74128 using GRASS GIS 6.4.0 (2010) software.

Sampling Methods

Water quality sampling data were collected at five sampling stations within Oologah Lake and at three sites outside of the lake on a regular basis since from January 2000 to December 2008 by U.S. Army Corps of Engineers Environmental Analysis and Compliance Branch, Tulsa District, personnel. Location descriptions and coordinates of the five stations are listed in Table 1. From 2000 through 2002, mostly bimonthly sampling trips were conducted, at the beginning of 2004 through to the end of the study period sampling was conducted on a monthly basis. Weather, or other unforeseen circumstances (i.e. mechanical problems), prevented some scheduled sampling events from occurring and/or not all stations being sampled. Actual sampling dates and stations sampled in this study are listed in Appendix 1. Water samples were collected on the lake between 0900 hrs and 1500 hrs CST on each date listed in Appendix 1 by using a boat and GPS equipment to navigate to the sites and anchoring in the thalweg. All samples collected in bottles were placed on ice in an ice chest until delivered to the appropriate analysis lab.

Table 1. Oologah Lake primary water quality station identification numbers, location descriptions, and station coordinates for the 2000 – 2008 study period.

Primary Station Code	Sampling Station Code	Location Description	Coordinates[1]
1OOLOKN0120	OOL-1	-Damsite at buoy line over river channel -Most downstream site of the lake	36:25.340N 95:40.675W
1OOLOKN0240	OOL-2	-Upstream of OOL-1 -By Goose Island	36:29.619N 95:36.614W
1OOLOKN0241	OOL-3	-Upstream of OOL-2 -Approx. 1 km downstream of Wignon Bridge	36:33.296N 95:35.965W
1OOLOKN0126	OOL-4	-Upstream of OOL-3 -West of Highway 28 Bridge	36:35.993N 95:34.550W
1OOLOKN0127	OOL-5	-Mouth of Double Creek Cove -Most upstream site of the lake	36:38.978N 95:34.760W

[1] (USACE, 2002)

The U.S. Army Corps of Engineers Environmental Analysis and Compliance Branch personnel sampled for various water quality parameters; this study presents the analysis of the water quality parameters that have been previously researched and noted to be impacted by zebra mussels in areas that they first invaded the United States for comparison purposes. Water clarity changes, dissolved oxygen concentrations, ammonia concentrations, phosphorus concentrations, and chlorophyll *a* concentrations have been noted to be impacted by zebra mussel invasions (Holland, 1993; Holland *et al.*, 1995; Johengen *et al*., 1995; Effler *et al*., 1996; Effler *et al*., 2004; Yu and Culver, 2000).

Secchi disk transparency was measured using the standard procedures (Weztel and Likens, 2000), recorded in meters. Turbidity (measured in Nephelometric Turbidity Units), and dissolved oxygen levels (mg/l) were recorded using either a Hydrolab or Yellow Springs Instruments sonde unit and data logger, then downloaded to a computer and saved as a Microsoft Excel file. Surface water samples were taken at 0.5 meters in container appropriate bottles (see Table 2) using either the grab technique (hand grab samples over the side of the boat) or a Van Dorn water sampler. Analyses of total suspended solids, total ammonia, and total phosphorus samples collected during this study were conducted by the City of Tulsa, Department of Public Works Quality Assurance Lab in Tulsa, Oklahoma. Tulsa District U.S. Army Corps of Engineers Environmental Analysis and Compliance Branch personnel determined chlorophyll *a* concentrations fluorometrically using EPA Method 445.0.

Table 2. Analysis method, detection limits, and container types for each water quality parameter.

Parameter	**Method**[1]	**Detection Limit**	**U.S. EPA STORET Parameter Code**	**Container Type**
Turbidity	Sonde unit[2]	N/A	00076	N/A
Dissolved Oxygen	Sonde unit[2]	N/A	00299	N/A
Total Phosphorous[3]	EPA 365.2 SM4500PE[5]	0.009 mg/l	00665	Clear HDPE
Total Ammonia[3]	EPA 350.1	varied[6]	00610	Clear HDPE
Total Suspended Solids[3]	EPA 160.2	4.00 mg/l	00530	Clear HDPE
Chlorophyll *a*[4]	EPA 445.0	0.10 μg/l	32209	Amber HDPE

[1] Analysis methods described in Standard Methods (SM) for the Examination of Water and Wastewater (APHA 1992), and Methods for the Analysis of Water and Wastes (USEPA 1979)

[2] Turbidity and Dissolved Oxygen levels were measured using a YSI or Hydrolab sonde unit

[3] Analysis performed by City of Tulsa Quality Assurance Laboratory (CoTQA), Tulsa, OK 74127

[4] Analyses performed by Tulsa District Personnel

[5] CoTQA started using SM4500PE in Sept 2007 for analysis of phosphorus

[6] Detection limits changed throughout the study period: Apr 2000 – Aug 2000 (0.06 mg/l); Oct 2000 (0.023 mg/l); Apr 2001 – Oct 2001, Aug 2005 – Oct 2005 (0.05 mg/l); Oct 2002, May 2005 – Jul 2005 (0.03 mg/l); Apr 2004 – Oct 2004 (0.038 mg/l); and Apr 2007 – Oct 2008 (0.10 mg/l).

Statistical Analysis

Analyses of Covariance (ANCOVA), statistical significance at α=0.05, were performed using PC SAS Version 9.2 (SAS Institute, Cary, NC). ANCOVAs were conducted with PROC MIXED, and protected post hoc pair-wise comparisons were performed with a DIFF option in an LSMEANS statement. Separate analyses for each sampling station were performed, along with an analysis of all stations combined. Year and month (and station, when appropriate) were considered random blocking effects in the model. For the purposes of this analysis, only the samples collected in April through October, pre- and post-zebra mussel invasion were used; these months were selected because the water temperature during these months were more conducive to zebra mussel metabolic activity, growth, and higher filtration rates (McMahon, 1996; MacIsaac, 1996; Reeders and Vaate, 1990; Mackie and Schloesser, 1996; Claudi and Mackie, 1994). The samples collected during 2003 and 2006 were excluded from analysis to account for the system adjustment to the introduction and population die-off, respectively. Zebra mussels were first identified in Oologah Lake in June 2003; therefore, the water quality data from 2000 – 2002 represent the control and is designated as the before treatment of zebra mussel invasion results in the analysis (noted as "*Before*"). A significant die-off of zebra mussels in Oologah Lake was noted in 2006 (Boeckman and Bidwell, 2008); therefore, the years after the arrival of zebra mussels were analyzed as two separate treatment categories: during treatment and after treatment of zebra mussel invasion. Data from 2004 and 2005 are designated as during the well-established and thriving zebra mussel population (noted as "*During*"); data from 2007 and 2008 are designated as after the zebra mussel population crash (noted as "*After*").

Hydraulic residence time (also referred to as retention time or flushing rate) is an important parameter in a lake system and should be considered when studying and analyzing nutrient dynamics within a lake (Horne and Goldman, 1994; Kõiv *et al.*, 2010). The length of time that the water is retained in the lake directly impacts time that the biological and chemical reactions have to occur in the system (Cole and Pace, 1998) and also impacts where dissolved and suspended substances are located within the system at a given time (Rueda *et al.*, 2006). Oologah Lake is a reservoir with controlled releases by the U.S. Army Corps of Engineers, Tulsa District from the project dam for the purposes of navigation and flood control; therefore, in this study, the hydraulic residence time was used as the covariate in the ANCOVA.

Hydraulic residence time is determined by dividing the lake volume by the inflow or outflow (Horne and Goldman, 1994); dividing the lake volume by outflow is a common calculation for hydraulic residence time (Rueda *et al.*, 2006; Cole and Pace, 1998) and was used in this study. Because the releases from Oologah Lake vary depending on flood control needs and navigation needs further downstream of the dam, the hydraulic residence time was calculated in days. Lake volumes and release volumes were provided by the U.S. Army Corps of Engineers, Hydrology and Hydropower Branch, Tulsa District; calculated hydraulic residence time for each sampling date is provided in Appendix 3.

CHAPTER IV

FINDINGS

Water quality parameter results (Appendix 2) analyzed in this study were preformed temporally lake-wide, as well as at each station sampled within the lake. Analyses of Covariance were performed using PC SAS Version 9.2 with hydraulic residence time (HRT) as the covariate. Statistical significance was determined at $\alpha=0.05$. The three levels of treatment (TRT) are defined as follows: *Before* for the 2000 – 2002 data; *During* for the 2004 – 2005 data; and *After* for the 2007 – 2008 data. P-values for all the ANCOVA results for each parameter are reported in Table 10. Fisher's post hoc pair-wise comparisons were performed on all ANCOVA statistically significant results; p-values for these comparisons are also found in Table 10. Boxplot diagrams and scatterplot graphs were created using Minitab Version 15.1.30.0 (Minitab Inc., State College, PA); blue triangles in the boxplot represent the treatment means.

Water Clarity

To measure water clarity impacts, Secchi depths, turbidity, and total suspended solids were analyzed. Zebra mussels have been reported to increase Secchi depth measurements. If zebra mussels have impacted Oologah Lake, expected results would be to observe an increase in water clarity during zebra mussel presence. A decrease in water clarity after the zebra mussel die-off in 2006 would be also be expected, showing the system returning back to pre-zebra mussel state and therefore have shallower water transparency measurements.

Descriptive statistics for Secchi depth for lake-wide and the individual five sampling stations are presented in Table 3. Before zebra mussel presence, lake-wide analysis of Secchi disk depth results ranged from 0.05 m to 1.40 m; the results ranged from 0.10 m to 1.55 m during zebra mussel presence. After the zebra mussel die-off, Secchi depth measurements ranged from 0.15 m to 1.65 m. Graphical summaries for the lake-wide results according to zebra mussel presence are presented in Figures 2 and 3. The increase in Secchi depths during zebra mussel presence is most notable during the months of April through July (Figure 3). However, the highest Secchi depth measurement is observed at OOL-1 for the August 2007, after the die-off. Overall, lake-wide Secchi depth mean results increased after zebra mussel arrival and decreased after their die-off; however, there was no significant difference (p=0.3305) among the treatment (*Before*, *During*, and *After*) means (Table 10).

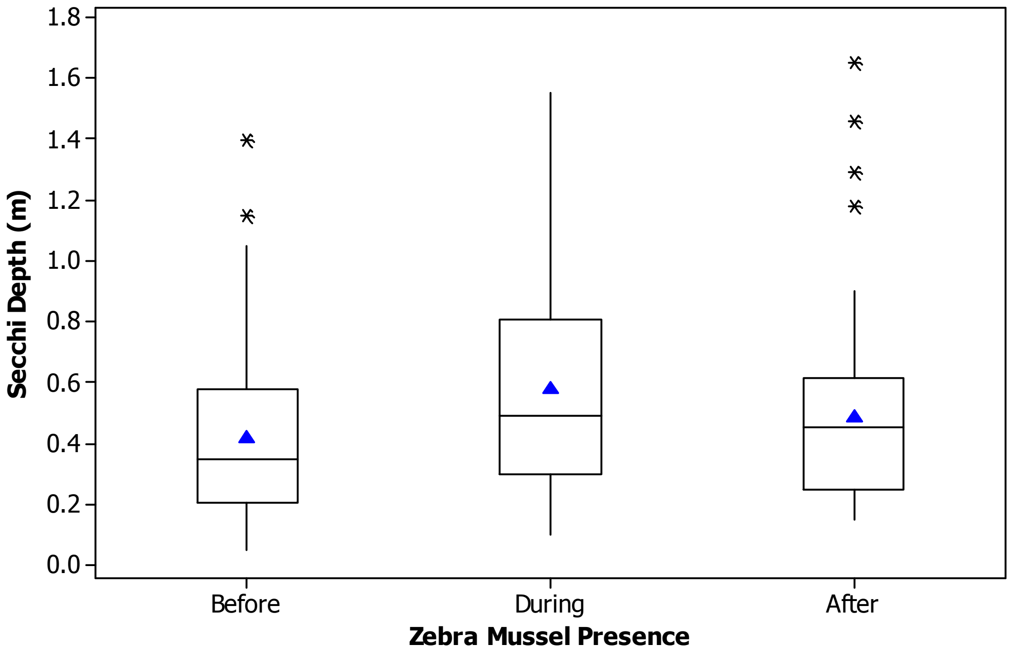

Figure 2. Boxplot of Secchi depth (m) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

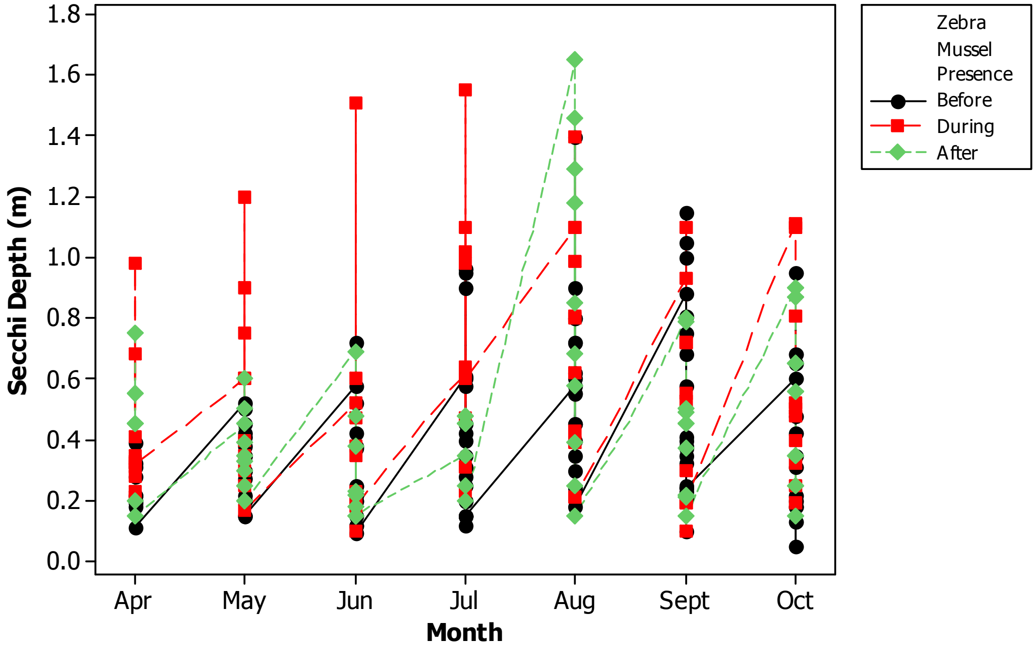

Figure 3. Scatterplot of Secchi depth (m) for all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Secchi depths at sampling station OOL-1 ranged from 0.31 m to 1.40 m during the *Before* treatment period and ranged from 0.31 m to 1.55 m for the *During* treatment period. The *After* treatment Secchi depth measurements ranged from 0.23 m to 1.65 m. Graphical summaries for the OOL-1 Secchi depth results are presented in Figures 4 and 5. As observed for the lake-wide analysis, an increase in Secchi depth is seen during the zebra mussel presence, most notably during April – July months (Figure 5). Statistically, there was no significant difference (p=0.4092) between Secchi depth treatment means at OOL-1 (Table 10).

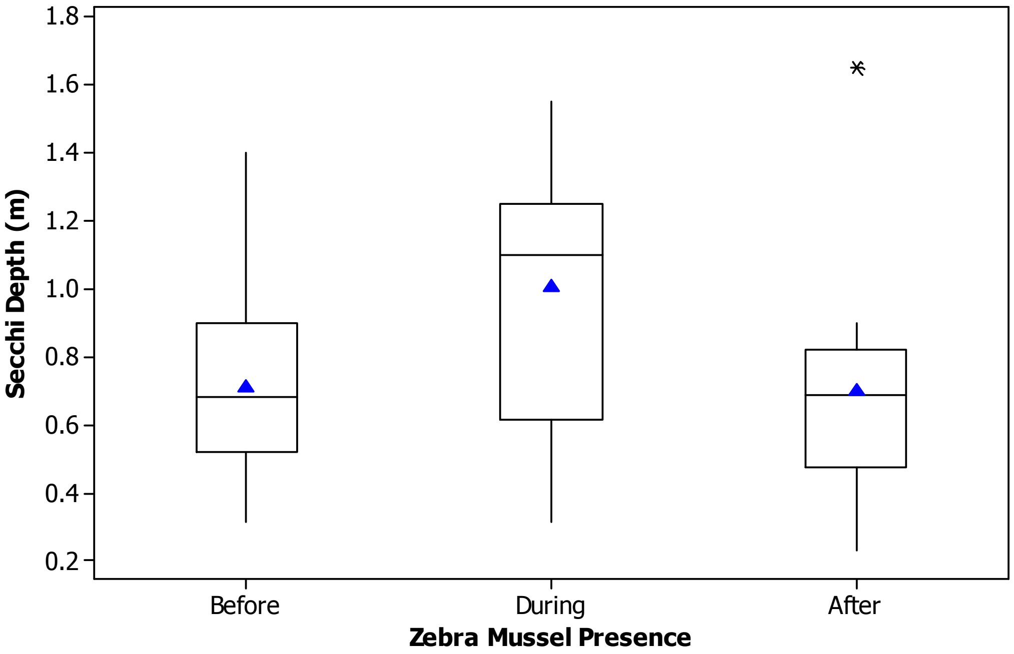

Figure 4. Boxplot of Secchi depth (m) variability across OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

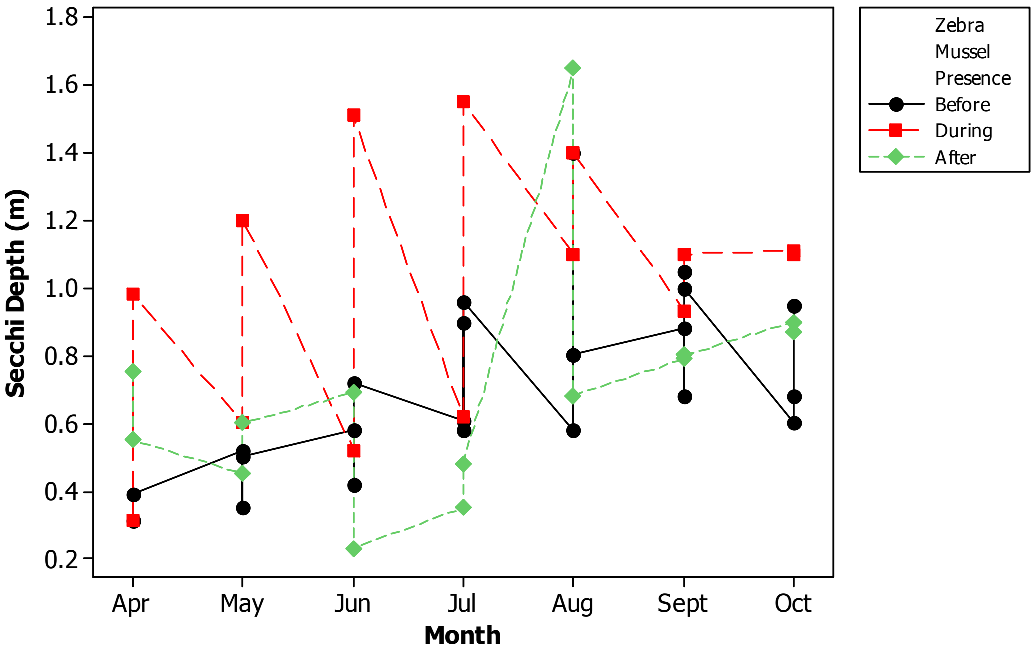

Figure 5. Scatterplot of Secchi depth (m) for OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Secchi depths at sampling station OOL-2 ranged from 0.05 m to 1.15 m during the *Before* treatment period and ranged from 0.28 m to 1.10 m for the *During* treatment period. The *After* treatment Secchi depth measurements ranged from 0.15 m to 1.46 m. Graphical summaries for the OOL-2 Secchi depth results are presented in Figures 6 and 7. As observed for the lake-wide analysis and OOL-1, an increase in Secchi depth at OOL-2 is seen during the zebra mussel presence, again most notably during April – July months. As seen at OOL-1, the highest Secchi depth measurement occurred during August 2007 for this station as well (Figure 7). Statistically, however, there was no significant difference (p=0.2537) between Secchi depth treatment means for OOL-2 (Table 10).

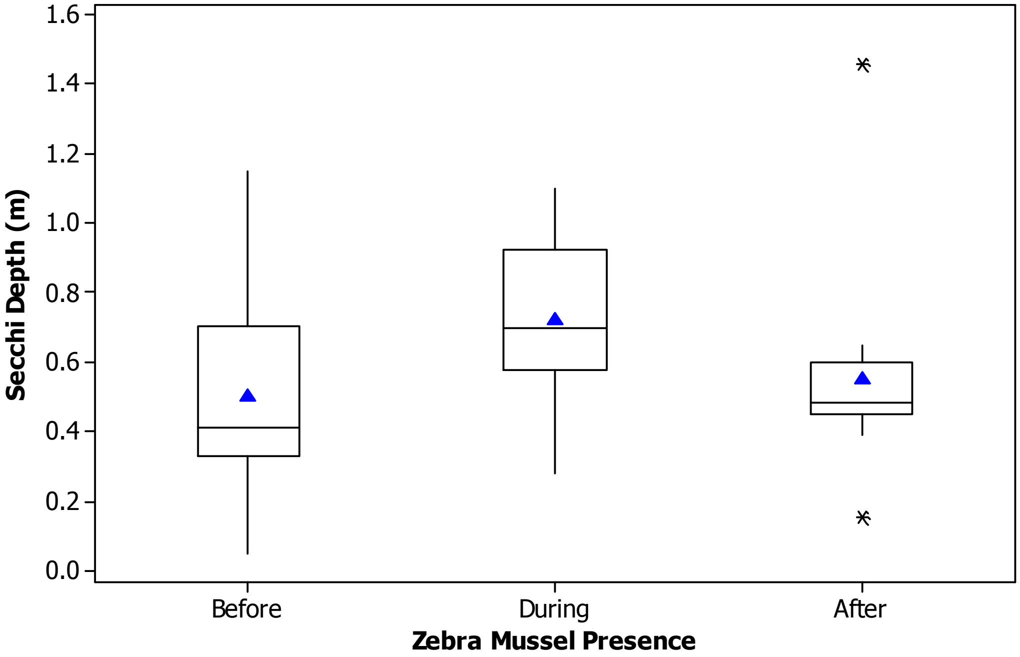

Figure 6. Boxplot of Secchi depth (m) variability across OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

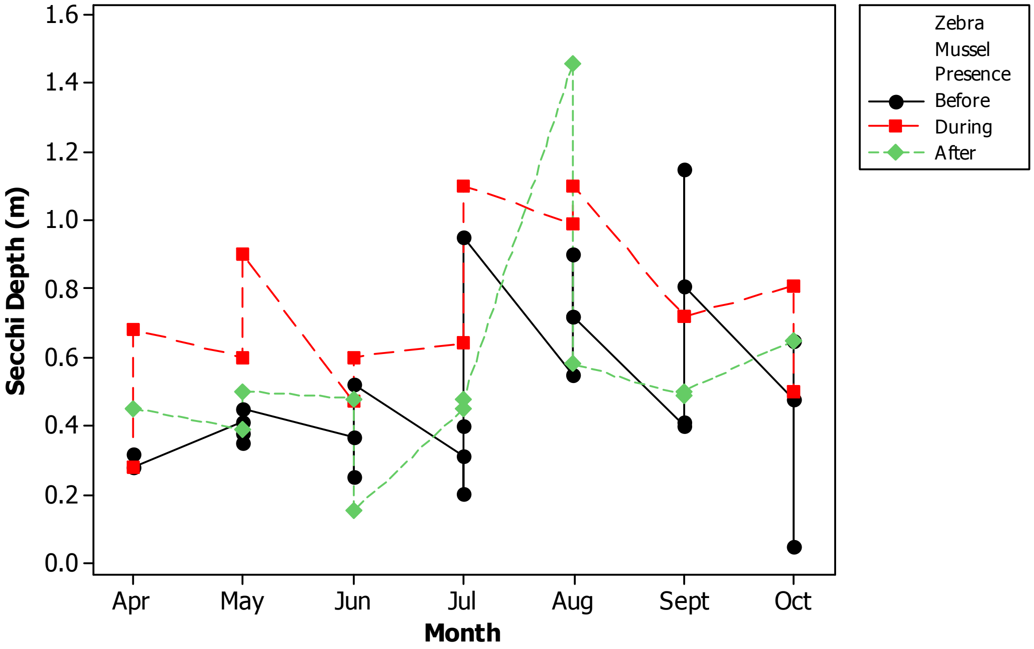

Figure 7. Scatterplot of Secchi depth (m) for OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Secchi depths at sampling station OOL-3 ranged from 0.20 m to 0.75 m during the *Before* period and ranged from 0.23 m to 1.02 m during the *During* period. After the zebra mussel die-off, the Secchi depth measurements ranged from 0.20 m to 1.29 m. Graphical summaries for the OOL-3 Secchi depth results are presented in Figures 8 and 9. An increase in Secchi depth maximum values and mean value is seen during the zebra mussel presence, with the most notable high increase during May and July of the zebra mussel presence study period (Figure 9). Again, the highest Secchi depth measurement was observed during the August 2007 sampling trip as seen at OOL-1 and OOL-2. There was no significant difference (p=0.2399) between Secchi depth treatment means for OOL-3 (Table 10).

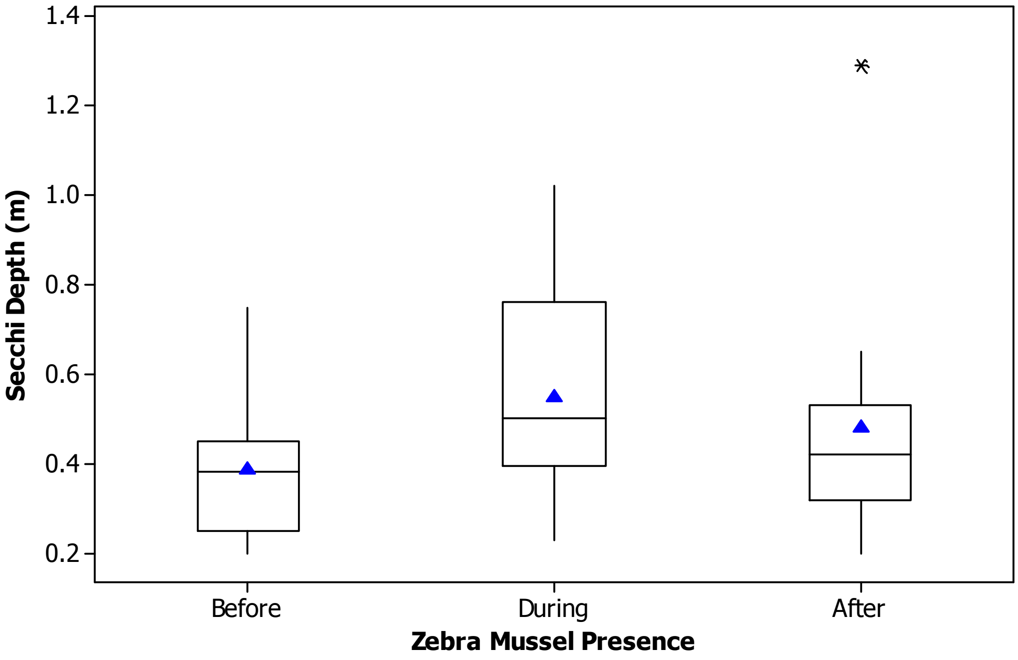

Figure 8. Boxplot of Secchi depth (m) variability across OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

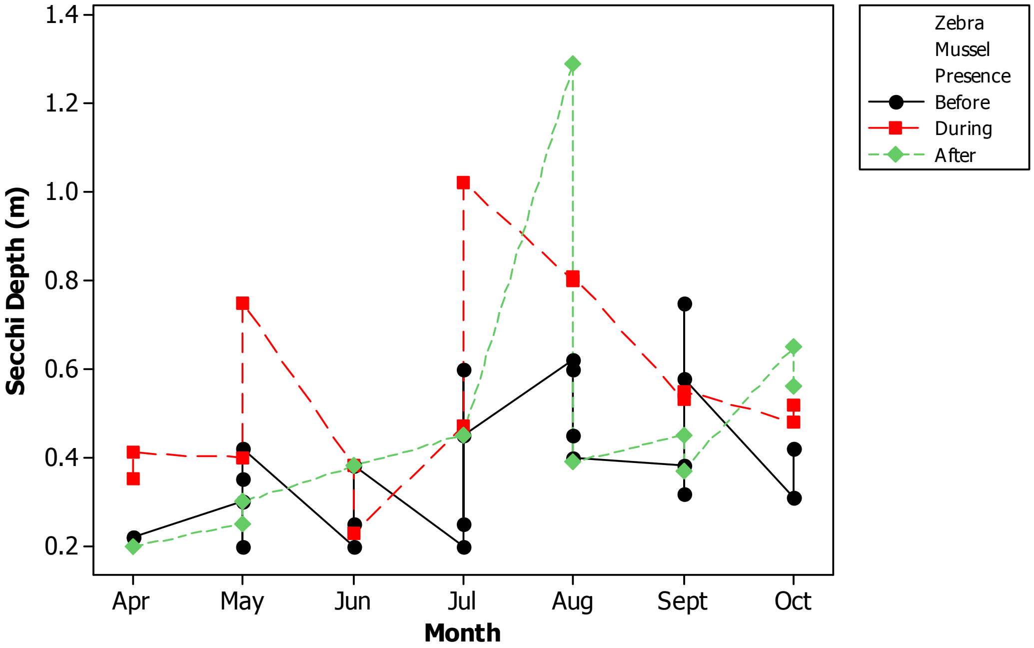

Figure 9. Scatterplot of Secchi depth (m) for OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Secchi depths at sampling station OOL-4 ranged from 0.12 m to 0.55 m during the *Before* period and ranged from 0.19 m to 0.98 m during the *During* period. After the zebra mussel die-off, the Secchi depth measurements ranged from 0.18 m to 1.18 m. Graphical summaries for the OOL-4 Secchi depth results are presented in Figures 10 and 11. Like the previous sampling stations discussed, an increase in Secchi depth *During* treatment mean is observed. However, unlike the previous stations, the mean for the *After* period of the study increases slightly instead of the typical decrease expected (Figure 10). There was no significant difference (p=0.4893) between Secchi depth treatment means for OOL-4 (Table 10).

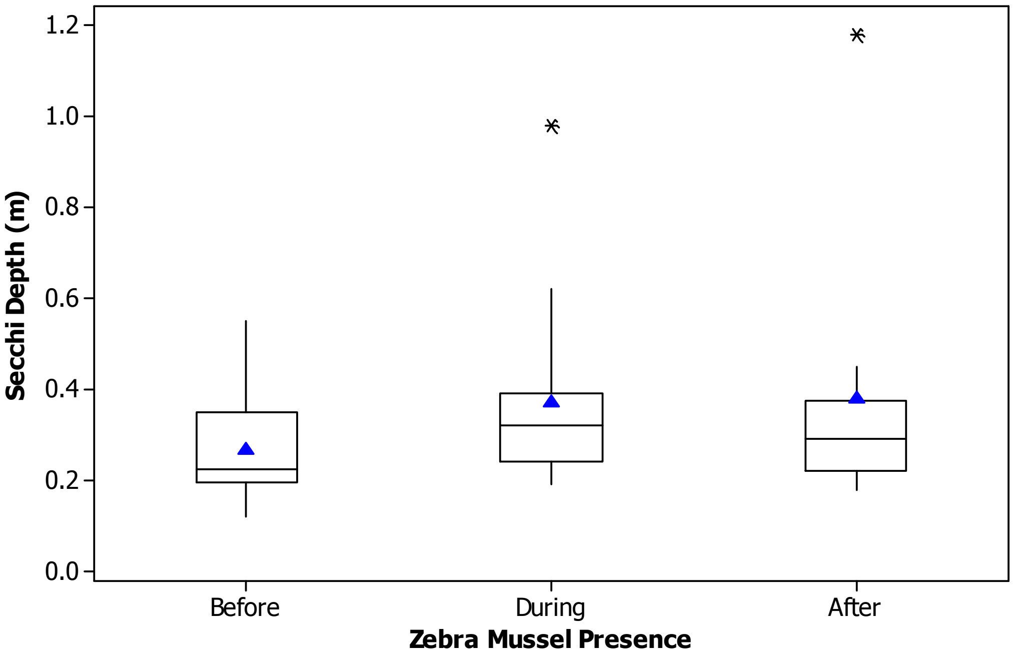

Figure 10. Boxplot of Secchi depth (m) variability across OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

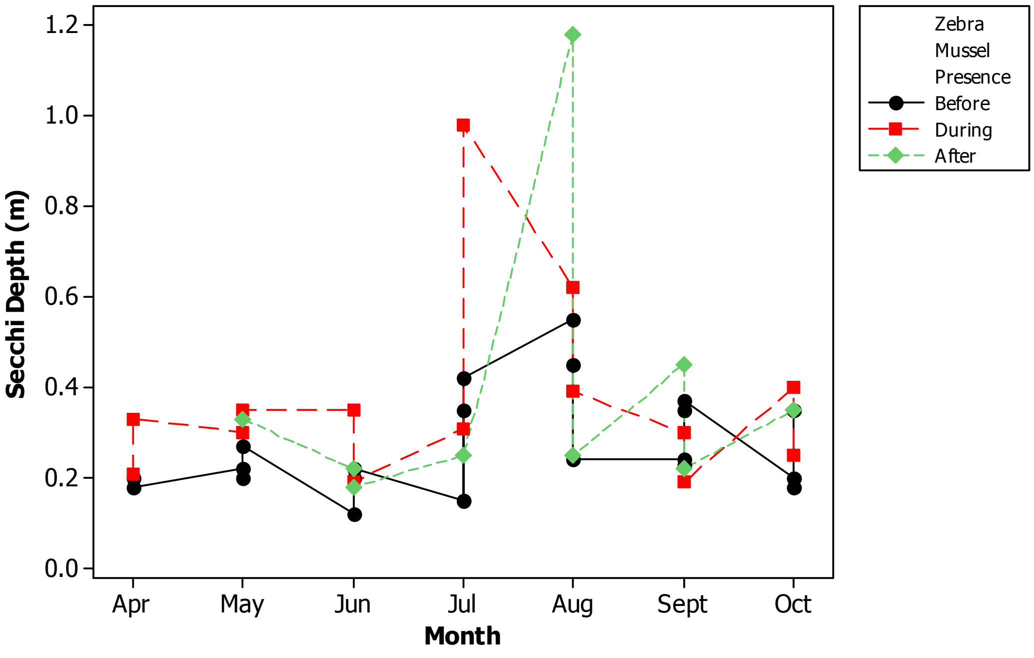

Figure 11. Scatterplot of Secchi depth (m) for OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Secchi depths at sampling station OOL-5 ranged from 0.09 m to 0.35 m during the *Before* period and ranged from 0.10 m to 0.60 m during the *During* period. After the zebra mussel die-off, the Secchi depth measurements ranged from 0.15 m to 0.85 m. Graphical summaries for the OOL-5 Secchi depth results are presented in Figures 12 and 13. An increase in Secchi depth measurement is observed after the zebra mussels arrival and the mean for the *After* period of the study only slightly increases, which was noted at OOL-4 as well; the August 2007 value in the *After* period may have increased the statistical mean for OOL-5 as noted for OOL-4 (Figures 12 and 13). There was no significant difference (p=0.4378) between Secchi depth treatment means for OOL-5 (Table 10).

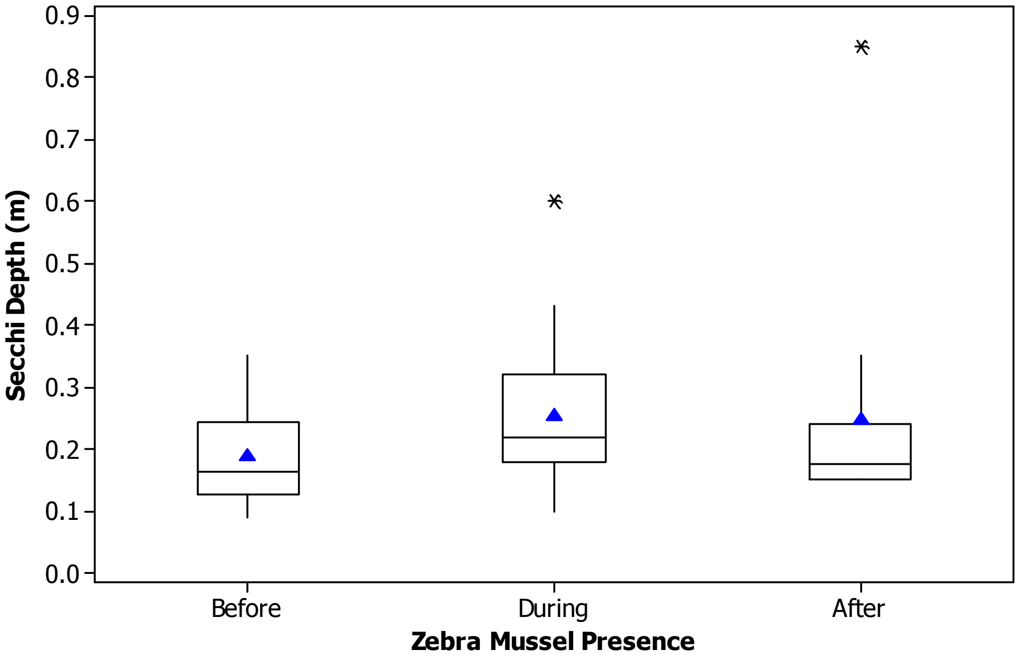

Figure 12. Boxplot of Secchi depth (m) variability across OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

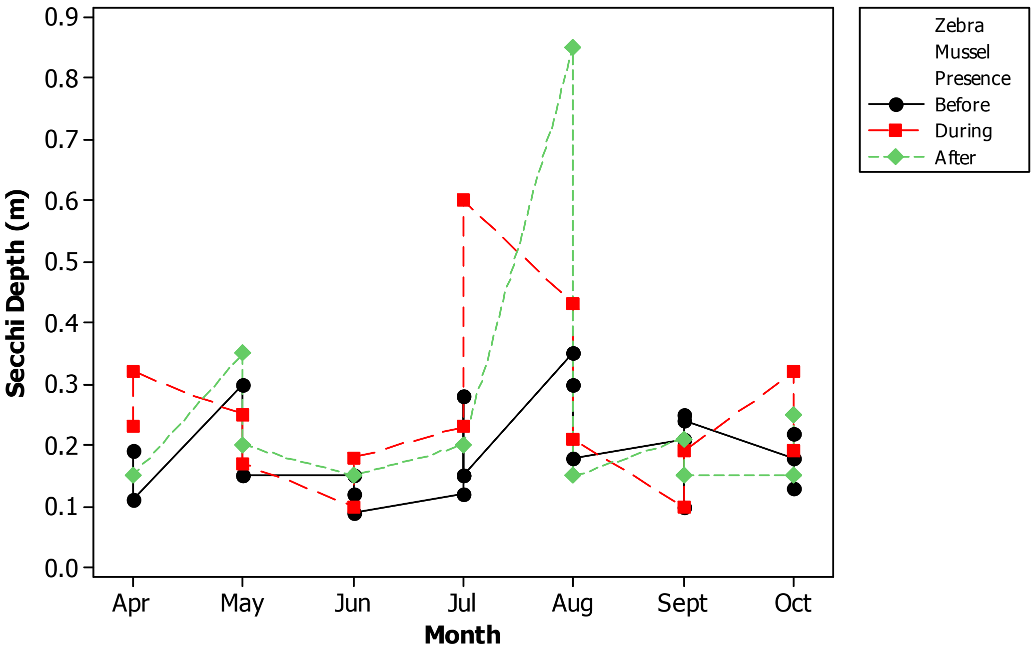

Figure 13. Scatterplot of Secchi depth (m) for OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Table 3. Descriptive statistics for Secchi depth (m) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	SE	Max	Min	Number of Obs.	Number of Obs. BDL[3]
Lake-wide						
Before	0.41333	0.024572	1.40	0.05	114	0
During	0.57900	0.042906	1.55	0.10	70	0
After	0.48306	0.040347	1.65	0.15	62	1
OOL-1						
Before	0.70696	0.05459	1.40	0.31	23	0
During	1.00214	0.10002	1.55	0.31	14	0
After	0.69929	0.09016	1.65	0.23	14	0
OOL-2						
Before	0.50125	0.05330	1.15	0.05	24	0
During	0.72214	0.06391	1.10	0.28	14	0
After	0.54857	0.07714	1.46	0.15	14	0
OOL-3						
Before	0.38565	0.03273	0.75	0.20	23	0
During	0.55000	0.05822	1.02	0.23	14	0
After	0.47833	0.08202	1.29	0.20	12	0
OOL-4						
Before	0.26545	0.02361	0.55	0.12	22	0
During	0.36929	0.05530	0.98	0.19	14	0
After	0.37800	0.09275	1.18	0.18	10	0
OOL-5						
Before	0.18727	0.01552	0.35	0.09	22	0
During	0.25143	0.03559	0.60	0.10	14	0
After	0.24667	0.05750	0.85	0.15	12	0

[1] April – October months used in analysis

[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008

[3] BDL=Below Detection Limit

Turbidity was also analyzed for water clarity analysis for Oologah Lake during the study period and the levels observed are reported here to accompany the Secchi depth analysis. Descriptive statistics for lake-wide analysis and all five sampling stations analyses of turbidity are reported in Table 4. Before zebra mussel arrival, the lake-wide turbidity levels ranged from 4.1 NTU to 282.1 NTU; during zebra mussel presence, turbidity levels ranged from 3.2 NTU to 370.9 NTU. The *After* treatment turbidity levels ranged from -0.8 NTU to 150.8 NTU. A negative turbidity reading occurred only during the August sampling trip in 2007 at two sites (Appendix 2). Figures 14 and 15 present graphical summaries according to zebra mussel presence. Overall, lower turbidity levels are observed after zebra mussel arrival in 2003, except for the September 2004 reading observed at OOL-5 sampling station, the most upstream site of the lake. Statistically, there was no significant difference (p=0.1004) between turbidity treatment means in the lake-wide analysis (Table 10).

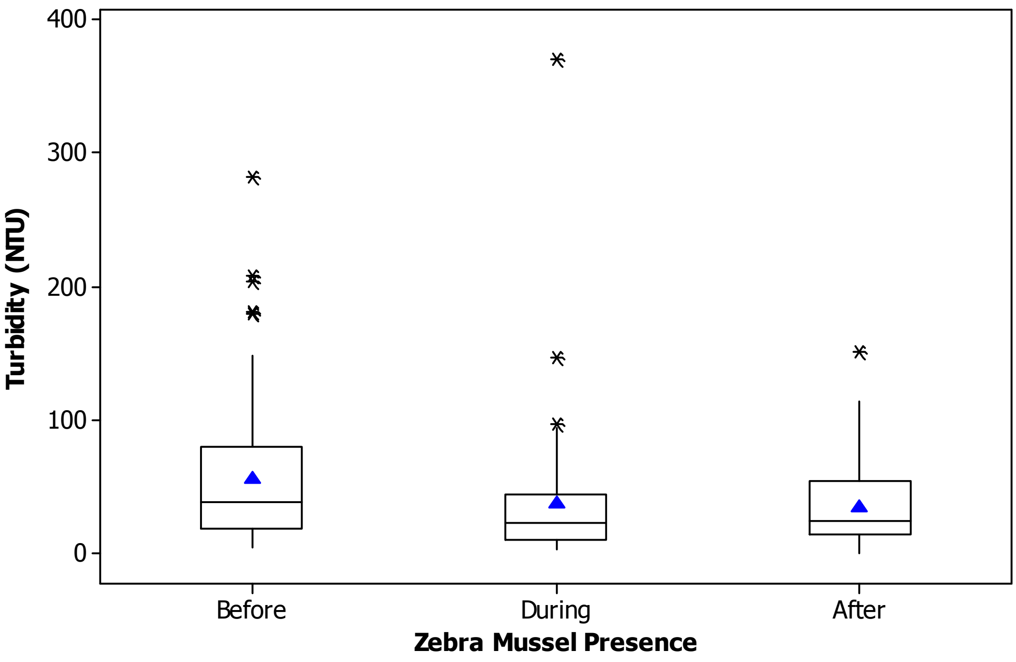

Figure 14. Boxplot of turbidity (NTU) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

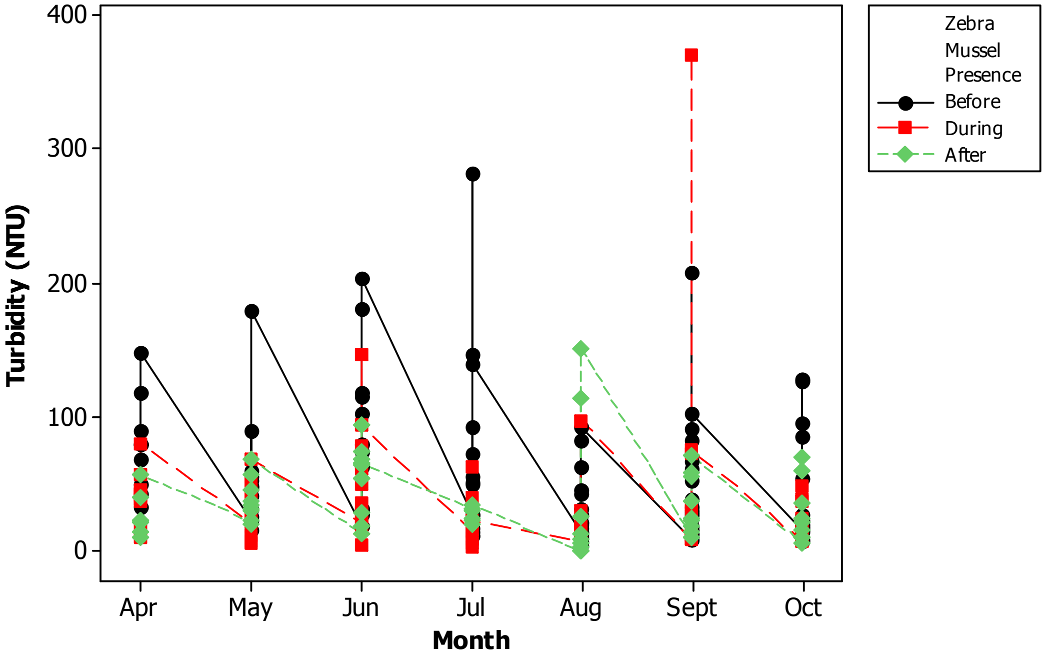

Figure 15. Scatterplot of turbidity (NTU) for all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Turbidity levels for OOL-1 sampling station ranged from 4.1 NTU to 49.5 NTU before zebra mussel arrival, and ranged from 3.2 NTU to 37.2 NTU during zebra mussel presence. After the die-off, the turbidity levels ranged from -0.8 NTU to 53.4 NTU. Both the maximum and mean turbidity levels decreased during the zebra mussel presence period at this sampling station; after the die-off, turbidity levels increased (Figures 16 and 17). There was, however, no statistical significant difference (p=0.2994) between turbidity treatment means at OOL-1 (Table 10).

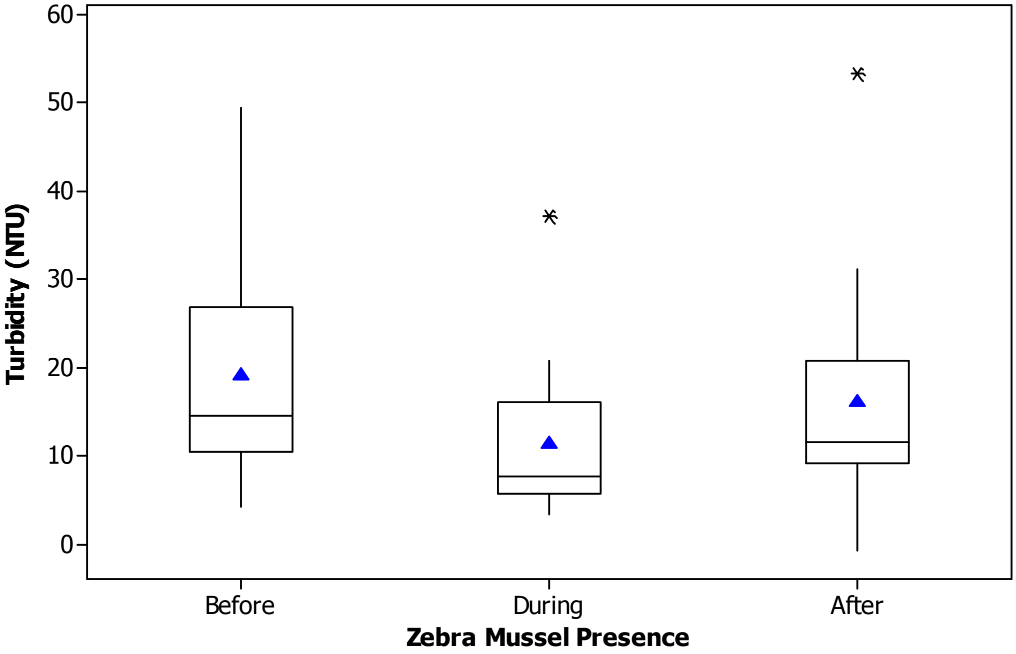

Figure 16. Boxplot of turbidity (NTU) variability across OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

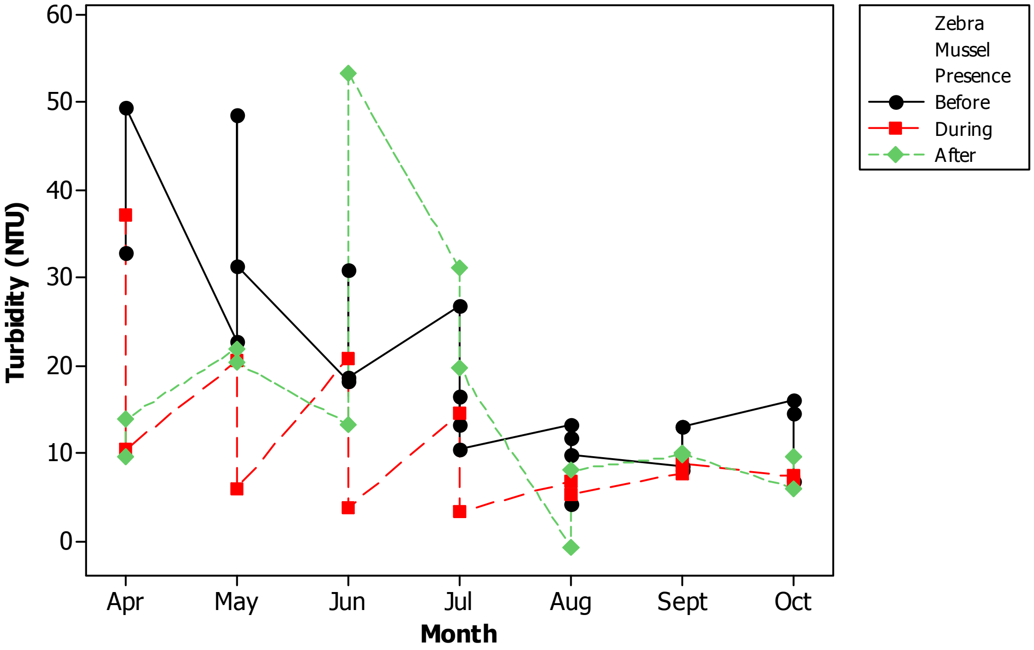

Figure 17. Scatterplot of turbidity (NTU) for OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Turbidity levels for OOL-2 sampling station ranged from 6.9 NTU to 79.3 NTU before zebra mussel arrival, and ranged from 6.8 NTU to 45.1 NTU during zebra mussel presence. After the die-off, the turbidity levels ranged from -0.4 NTU to 68.0 NTU. Like OOL-1, OOL-2 maximum and mean turbidity levels decreased during the zebra mussel presence period and increased after the die-off (Figures 18 and 19). There was, however, no statistical significant difference (p=0.2051) between turbidity treatment means at OOL-2 (Table 10).

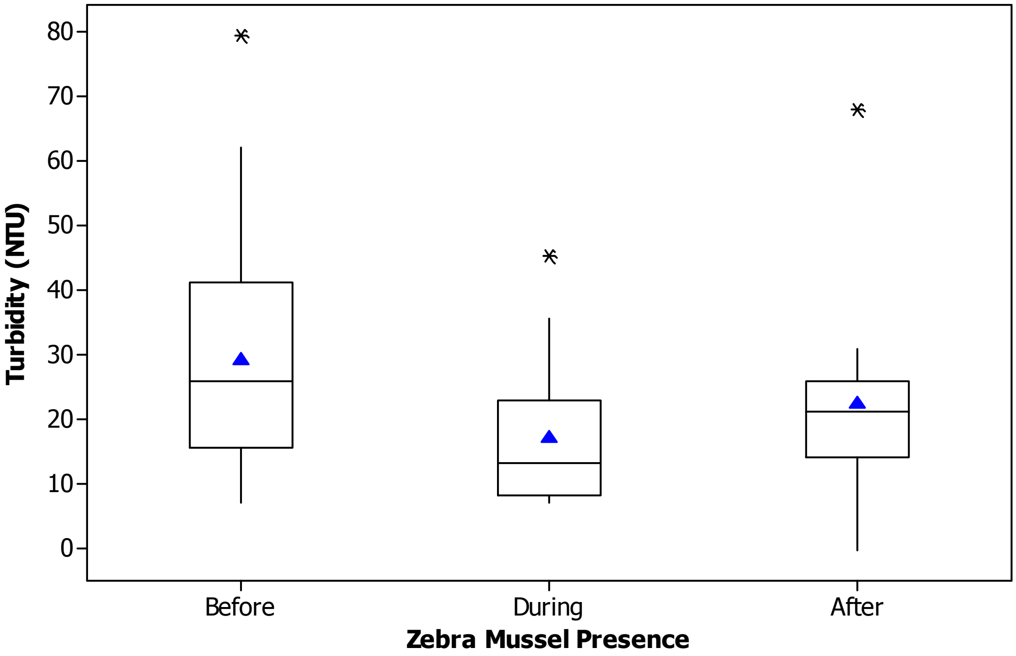

Figure 18. Boxplot of turbidity (NTU) variability across OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

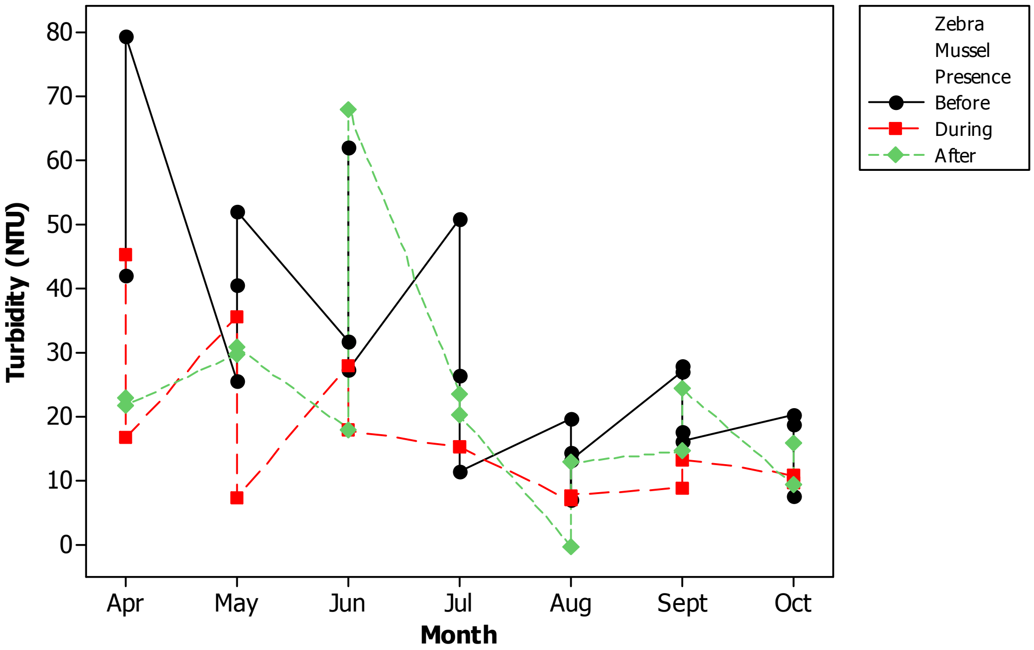

Figure 19. Scatterplot of turbidity (NTU) for OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Turbidity levels for OOL-3 sampling station ranged from 12.5 NTU to 95.3 NTU before zebra mussel arrival, and ranged from 5.4 NTU to 60.5 NTU during zebra mussel presence. After the die-off, the turbidity levels ranged from 0.1 NTU to 74.1 NTU. Like OOL-1 and OOL-2, OOL-3 maximum and mean turbidity levels decreased during the zebra mussel presence period and increased after the die-off (Figures 20 and 21). There was, however, no statistical significant difference (p=0.2416) between turbidity treatment means at OOL-3 (Table 10).

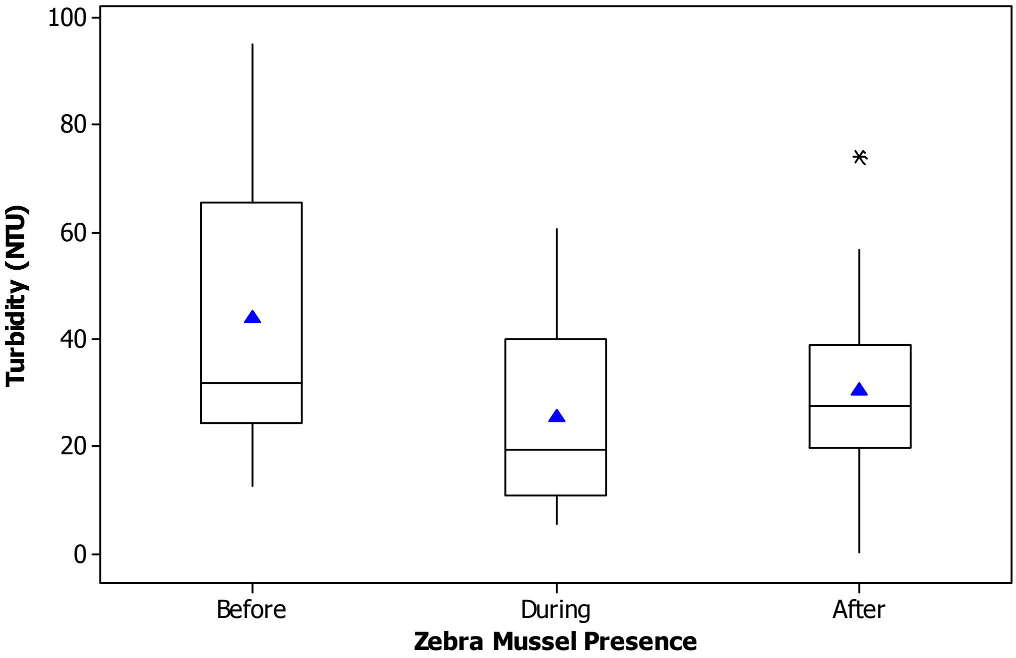

Figure 20. Boxplot of turbidity (NTU) variability across OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

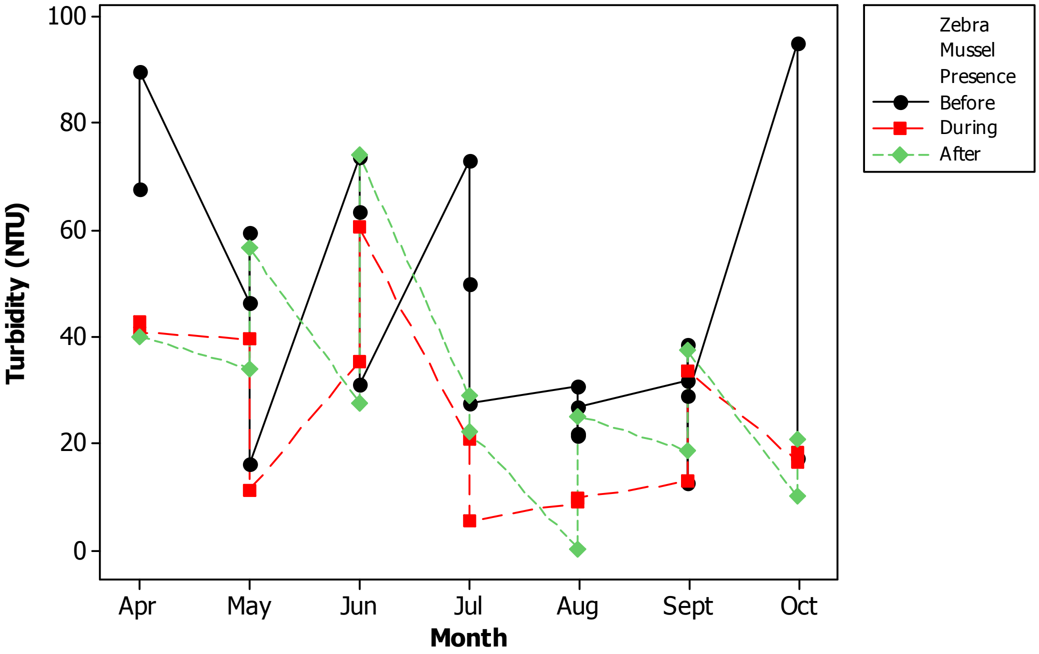

Figure 21. Scatterplot of turbidity (NTU) for OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Turbidity levels for OOL-4 sampling station ranged from 17.0 NTU to 118.5 NTU before zebra mussel arrival, and ranged from 8.2 NTU to 78.3 NTU during zebra mussel presence. After the die-off, the turbidity levels ranged from 1.9 NTU to 113.3 NTU. As seen with the previous sampling stations, OOL-4 maximum and mean turbidity levels decreased during the zebra mussel presence period and increased after the die-off (Figures 22 and 23). There was no statistical significant difference (p=0.1844) between turbidity treatment means at OOL-4 (Table 10).

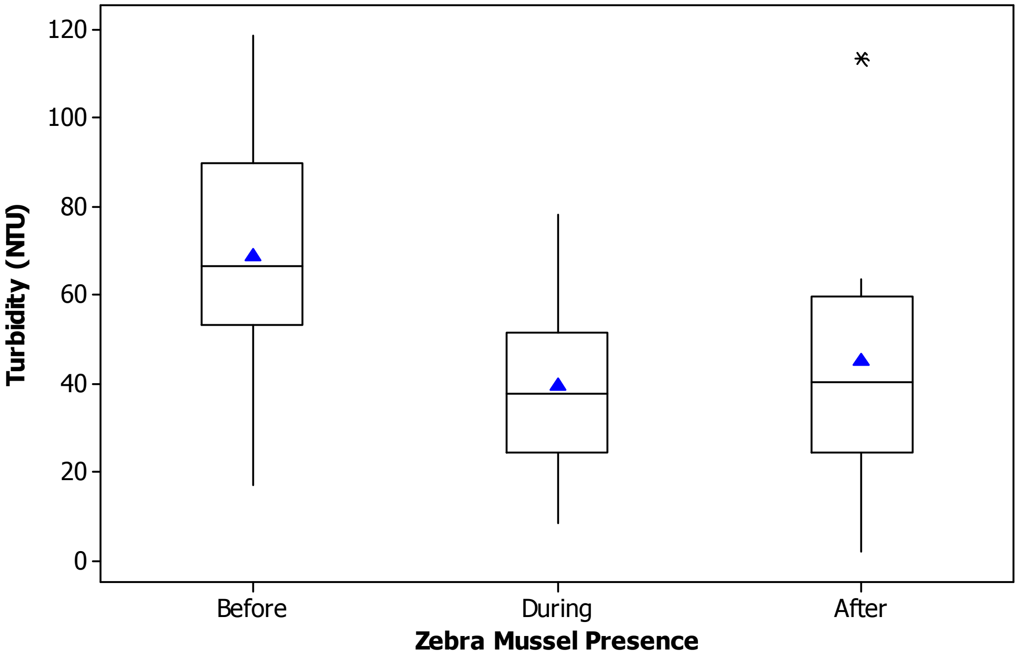

Figure 22. Boxplot of turbidity (NTU) variability across OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

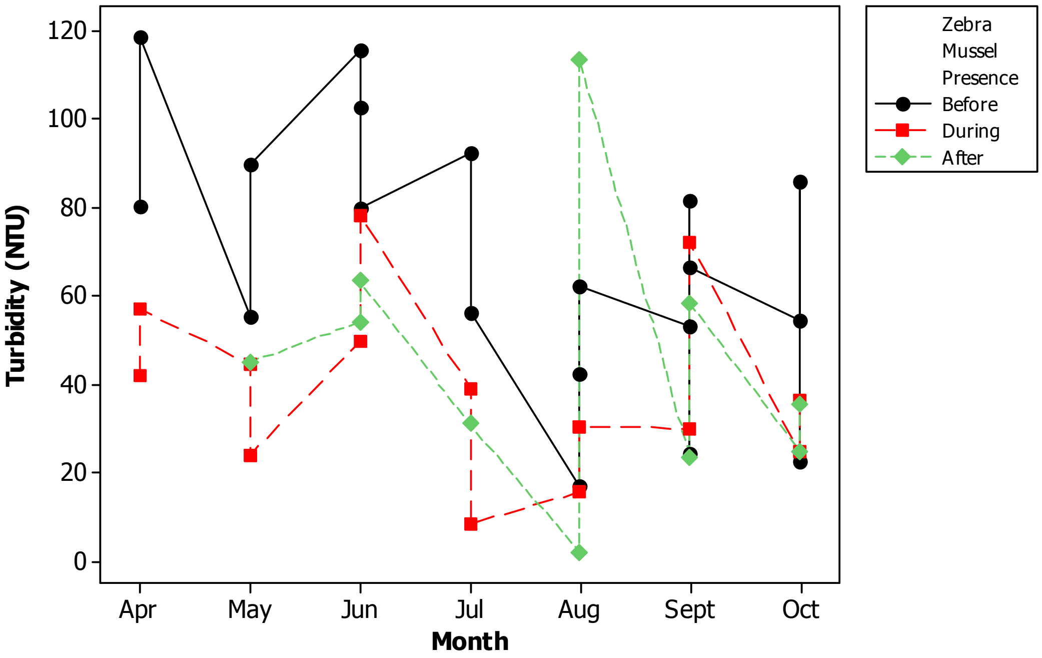

Figure 23. Scatterplot of turbidity (NTU) for OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Turbidity levels for OOL-5 sampling station ranged from 26.5 NTU to 282.1 NTU before zebra mussel arrival, and ranged from 18.4 NTU to 370.9 NTU during zebra mussel presence. After the die-off, the turbidity levels ranged from 5.1 NTU to 150.8 NTU. The maximum and mean turbidity levels for OOL-5 did not follow the expected decrease in level during zebra mussel presence followed by an increase after zebra mussel die-off; September 2004 at this site had the highest maximum value and the means continued to decrease over the treatment periods (Figures 24 and 25). No statistical significant difference (p=0.1222) between turbidity treatment means at OOL-5 (Table 10).

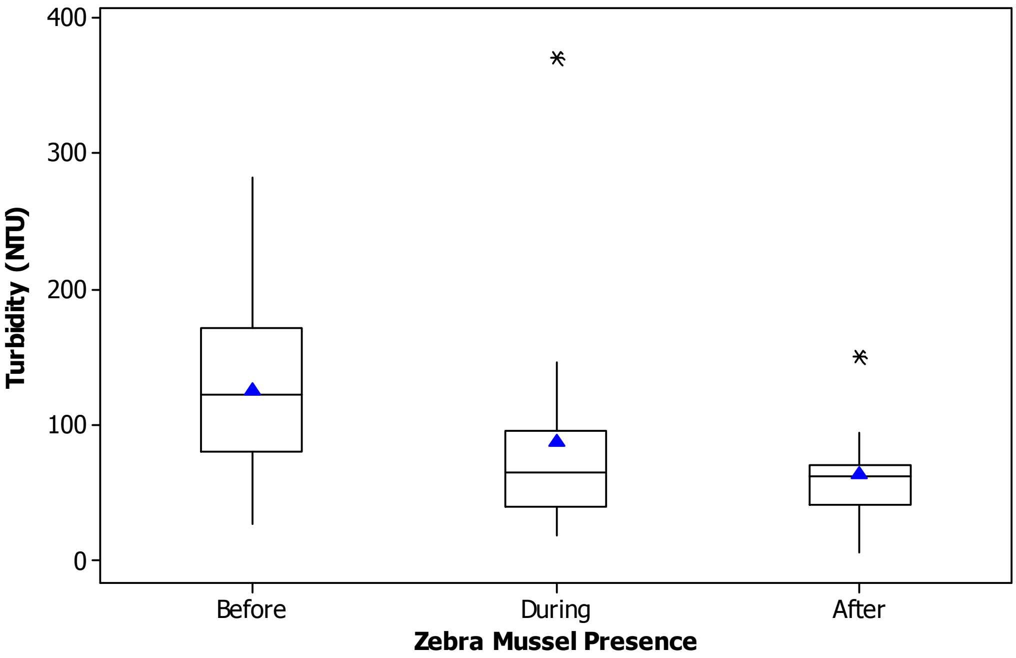

Figure 24. Boxplot of turbidity (NTU) variability across OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

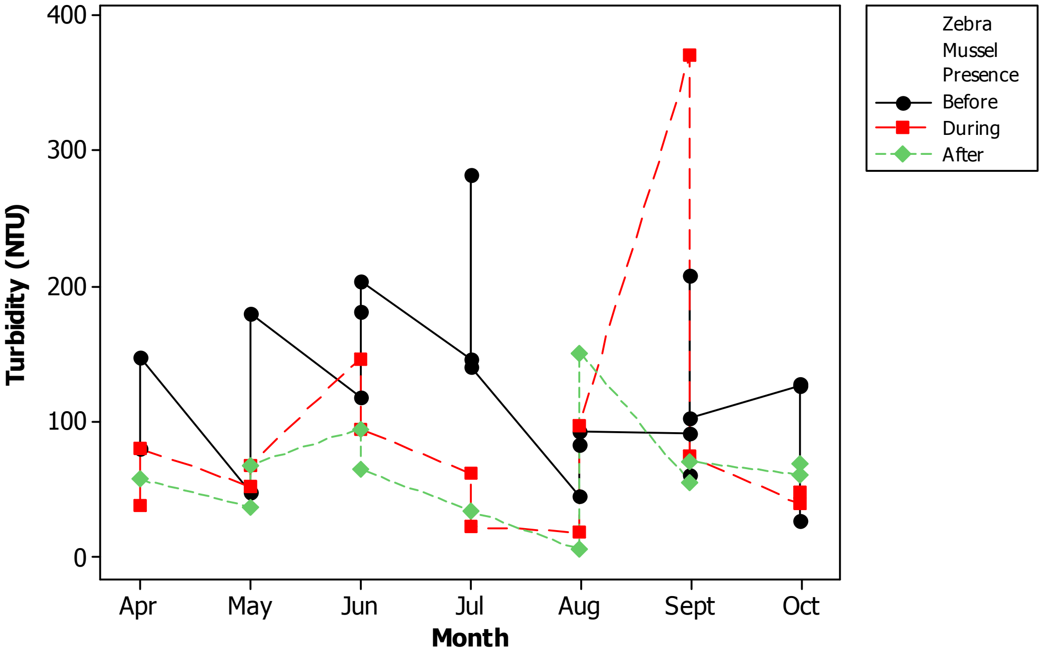

Figure 25. Scatterplot of turbidity (NTU) for OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Table 4. Descriptive statistics for turbidity values (NTU) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	**SE**	**Max**	**Min**	**Number of Obs.**	**Number of Obs. BDL[3]**
Lake-wide						
Before	55.1152	4.91623	282.10	4.10	105	0
During	36.1870	5.91306	370.90	3.20	69	0
After	34.0825	3.59449	150.80	-0.80	63	0
OOL-1						
Before	19.048	2.5728	49.50	4.10	23	0
During	11.343	2.4828	37.20	3.20	14	0
After	16.086	3.5620	53.40	-0.80	14	0
OOL-2						
Before	28.945	3.9665	79.30	6.90	22	0
During	17.046	3.3254	45.10	6.80	13	0
After	22.179	4.1447	68.00	-0.40	14	0
OOL-3						
Before	43.976	5.4503	95.30	12.50	21	0
During	25.421	4.4296	60.50	5.40	14	0
After	30.446	5.3271	74.10	0.10	13	0
OOL-4						
Before	68.400	6.8103	118.50	17.00	19	0
During	39.321	5.3528	78.30	8.20	14	0
After	44.990	9.6063	113.30	1.90	10	0
OOL-5						
Before	124.455	14.3147	282.10	26.50	20	0
During	86.436	23.6628	370.90	18.40	14	0
After	63.817	10.2283	150.80	5.10	12	0

[1] April – October months used in analysis
[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008
[3] BDL=Below Detection Limit

Total suspended solids (TSS) concentration levels were also analyzed for water clarity analysis for Oologah Lake during the study period and the levels observed are reported here to accompany the Secchi depth and turbidity analysis. Descriptive statistics for lake-wide analysis and the individual five sampling stations analyses of TSS are reported in Table 5. Before zebra mussel arrival, the lake-wide TSS levels ranged from 4.00 mg/l to 220.00 mg/l; the *During* treatment values ranged from 3.20 mg/l to 160.00 mg/l. The *After* treatment TSS levels ranged from 2.80 mg/l to 130.00 mg/l. All maximum TSS concentrations for each treatment period resulted from samples analyzed from OOL-5 (Table 10). Figures 26 and 27 present graphical summaries of TSS variability according to zebra mussel presence. Overall, TSS maximum and mean values decreased over treatment periods for the lake. Statistically, there was no significant difference (p=0.1179) between TSS treatment means.

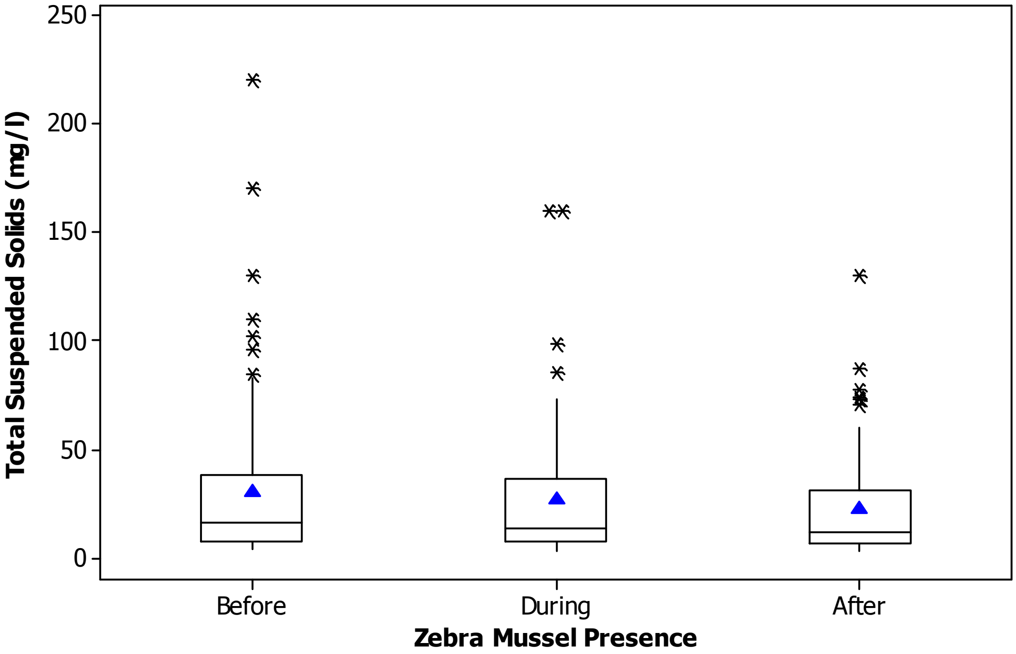

Figure 26. Boxplot of total suspended solids (mg/l) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

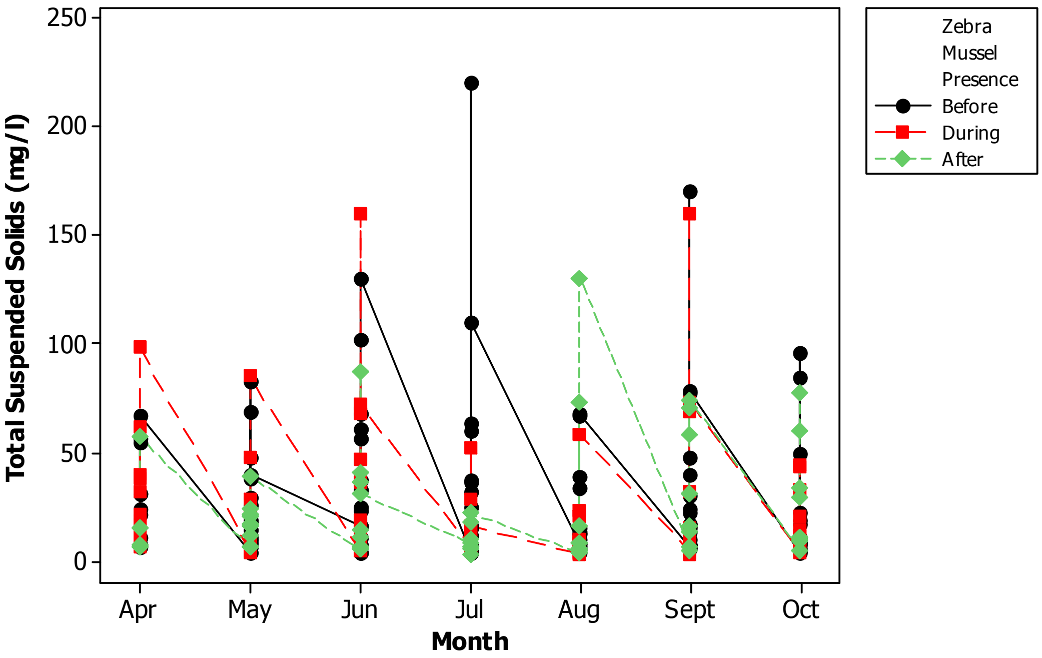

Figure 27. Scatterplot of total suspended solids (mg/l) for all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total suspended solid levels for OOL-1 sampling station ranged from below the detection limit (<4.00 mg/l) to 15.80 mg/l before zebra mussel arrival, and ranged from 3.20 mg/l to 17.00 mg/l during zebra mussel presence. After the die-off, the TSS levels ranged from 2.80 mg/l to 8.00 mg/l. Maximum TSS concentration value increased during zebra mussel presence; however, the mean TSS concentration decreased. After the die-off, both the maximum value and mean TSS levels continued to decrease (Figures 28 and 29). There was no statistical significant difference (p=0.3729) between TSS treatment means at OOL-1 (Table 10).

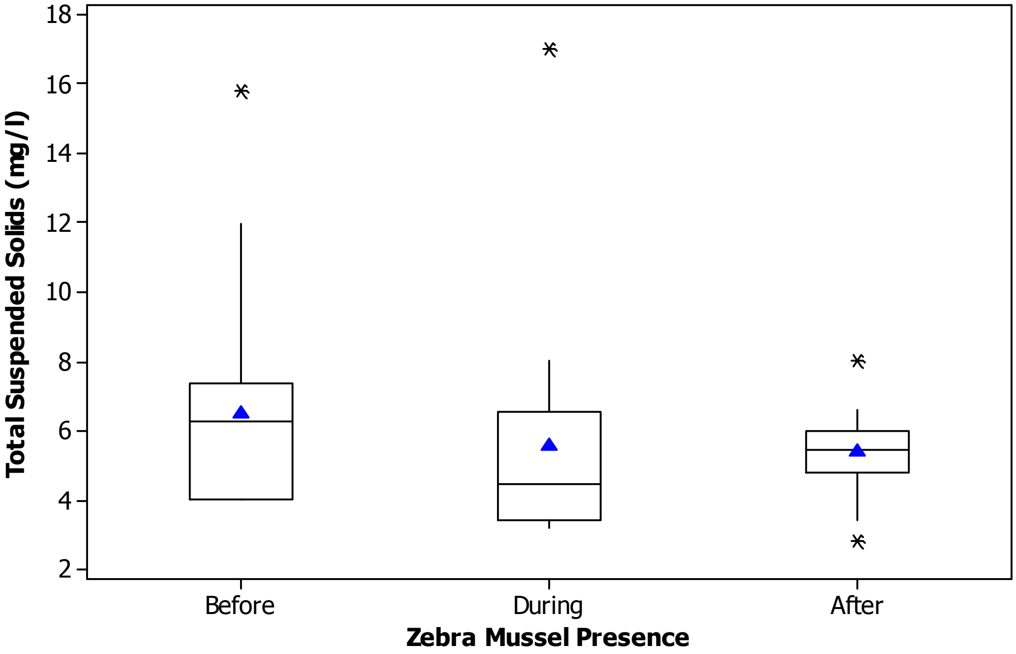

Figure 28. Boxplot of total suspended solids (mg/l) variability across OOL-1 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

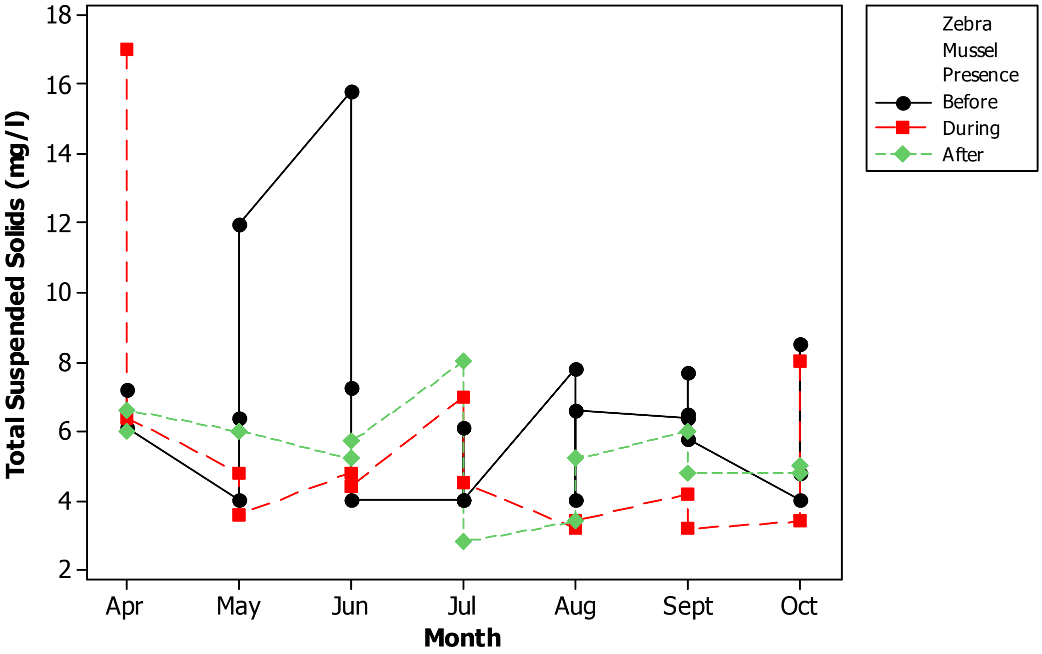

Figure 29. Scatterplot of total suspended solids (mg/l) for OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total suspended solid levels for OOL-2 sampling station ranged from below the detection limit (<4.00 mg/l) to 24.00 mg/l before zebra mussel arrival, and ranged from 5.40 mg/l to 21.00 mg/l during zebra mussel presence. After the die-off, the TSS concentration levels ranged from 4.60 mg/l to 20.00 mg/l. The maximum TSS values at this site decreased over treatment periods, the mean TSS concentration value during zebra mussel presence decreased and slightly increase after the die-off (Figures 30 and 31). There was no statistical significant difference (p=0.4461) between TSS treatment means at OOL-2 (Table 10).

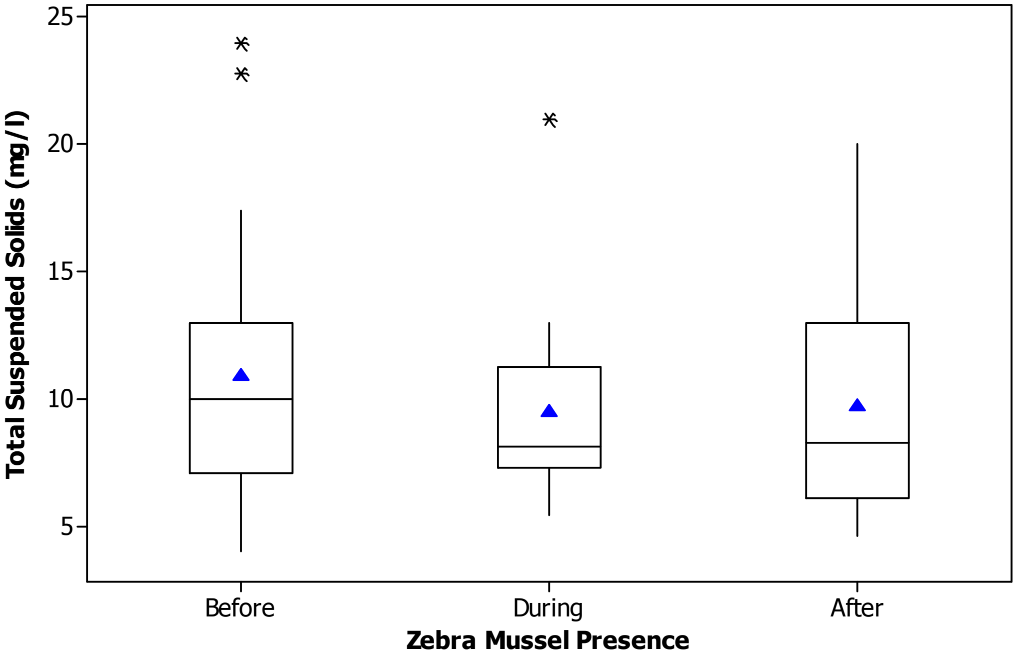

Figure 30. Boxplot of total suspended solids (mg/l) variability across OOL-2 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

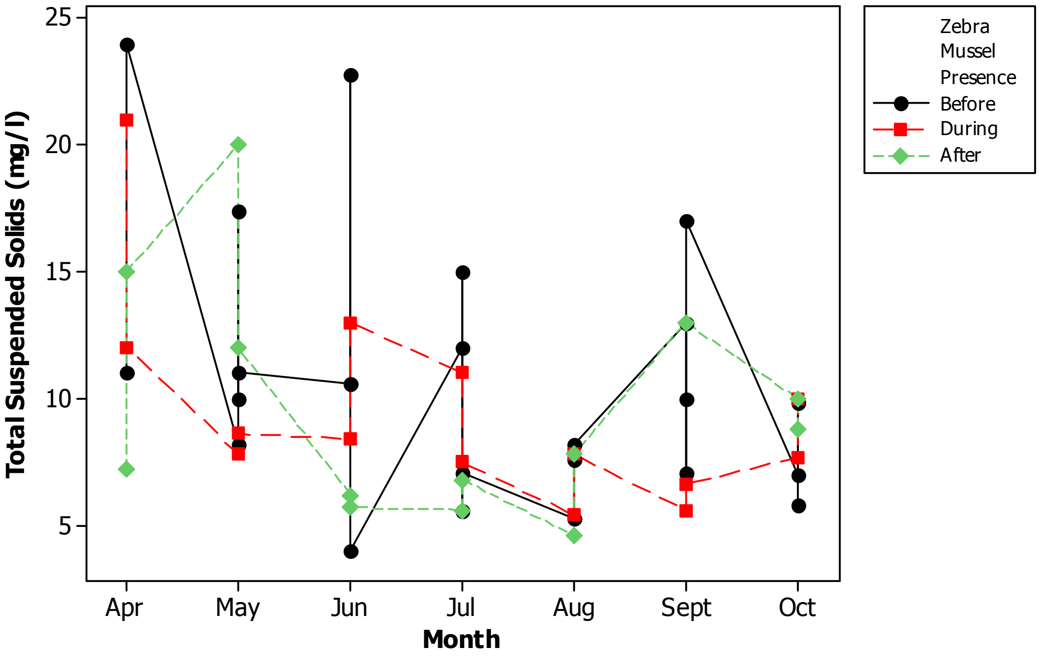

Figure 31. Scatterplot of total suspended solids (mg/l) for OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total suspended solid levels for OOL-3 sampling station ranged from 7.20 mg/l to 37.40 mg/l before zebra mussel arrival, and ranged from 5.50 mg/l to 47.00 mg/l during zebra mussel presence. After the die-off, the TSS levels ranged from 3.80 mg/l to 31.00 mg/l. OOL-3 results followed a similar pattern to OOL-1, the mean TSS concentration values decreased over treatment periods (Figures 32 and 33). There was no statistical significant difference (p=0.4118) between TSS treatment means at OOL-3 (Table 10).

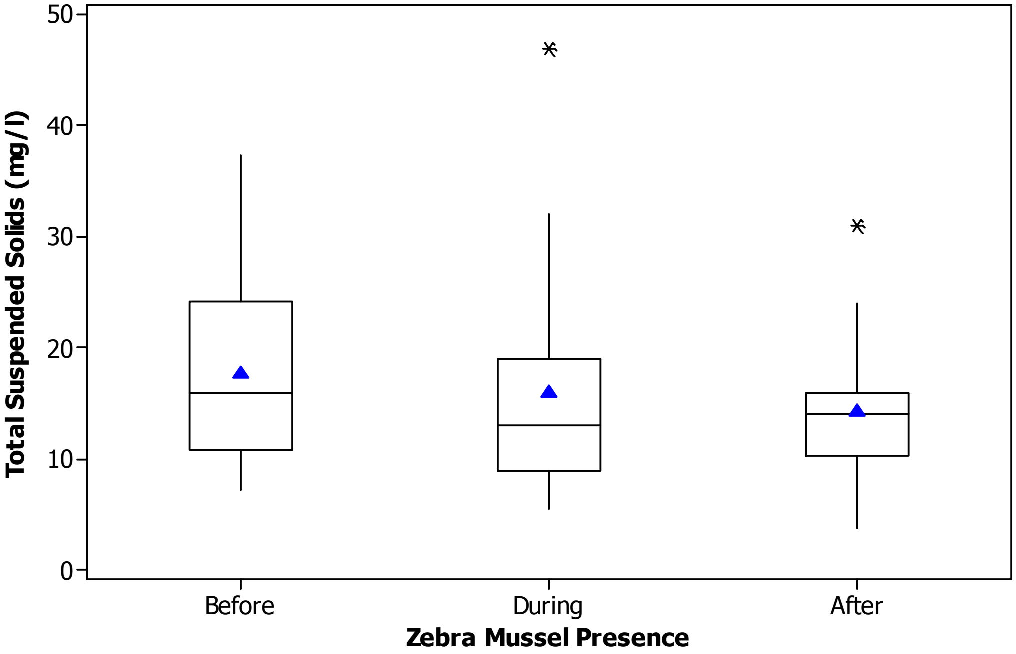

Figure 32. Boxplot of total suspended solids (mg/l) variability across OOL-3 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

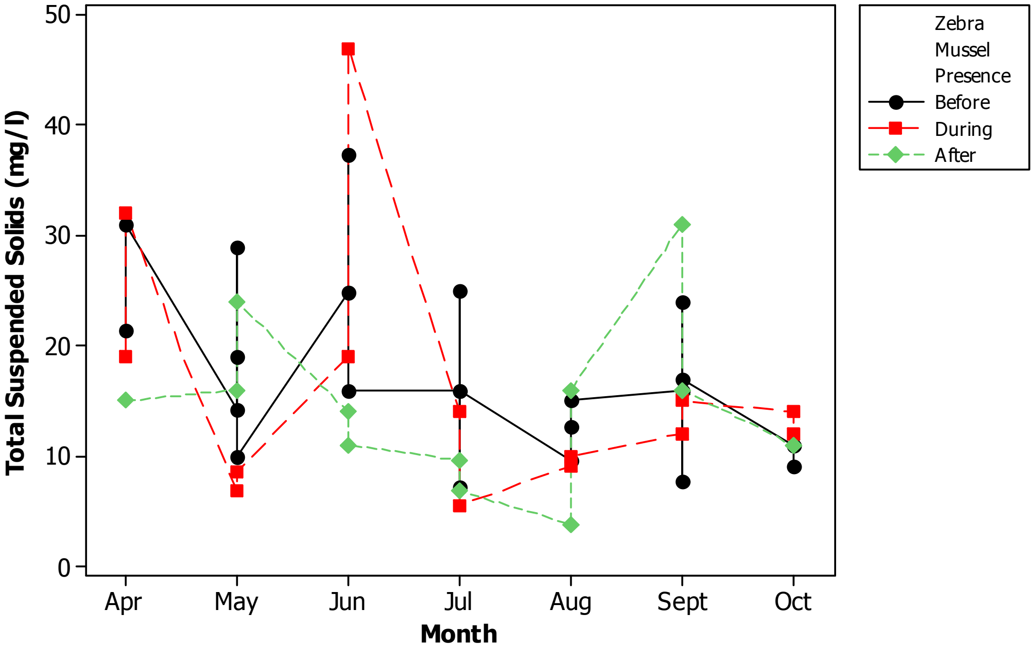

Figure 33. Scatterplot of total suspended solids (mg/l) for OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total suspended solid levels for OOL-4 sampling station ranged from 12.30 mg/l to 68.30 mg/l before zebra mussel arrival, and ranged from 8.00 mg/l to 69.00 mg/l during zebra mussel presence. After the die-off, the TSS levels ranged from 5.60 mg/l to 73.00 mg/l. The maximum TSS concentration values increased over treatment periods; however the means did decrease during zebra mussel presence and increased after the die-off (Figures 34 and 35). There was no statistical significant difference (p=0.9329) between TSS treatment means at OOL-4 (Table 10).

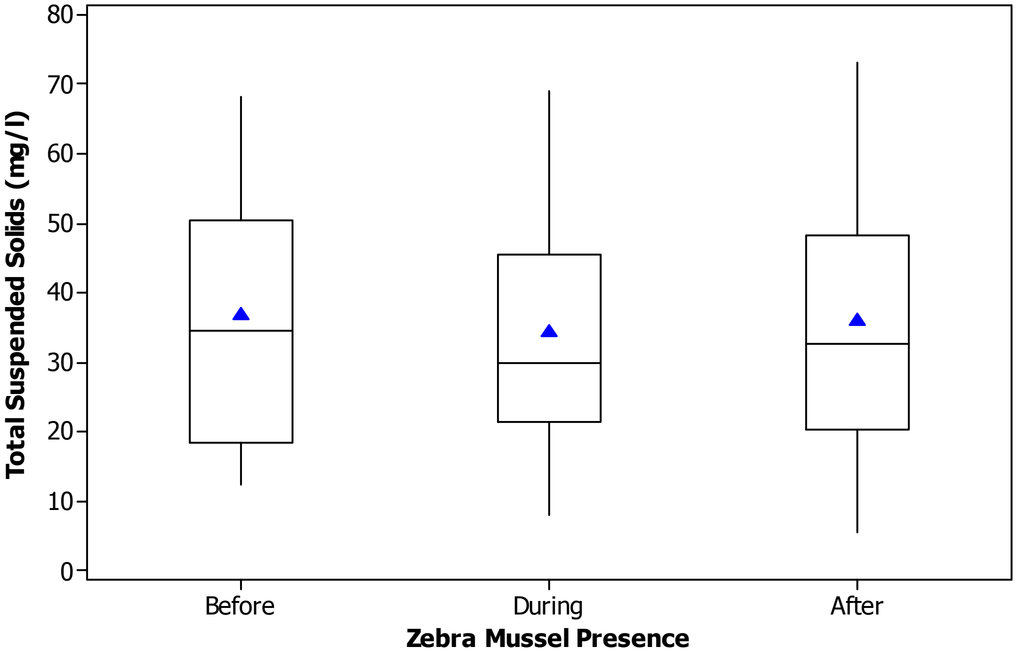

Figure 34. Boxplot of total suspended solids (mg/l) variability across OOL-4 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

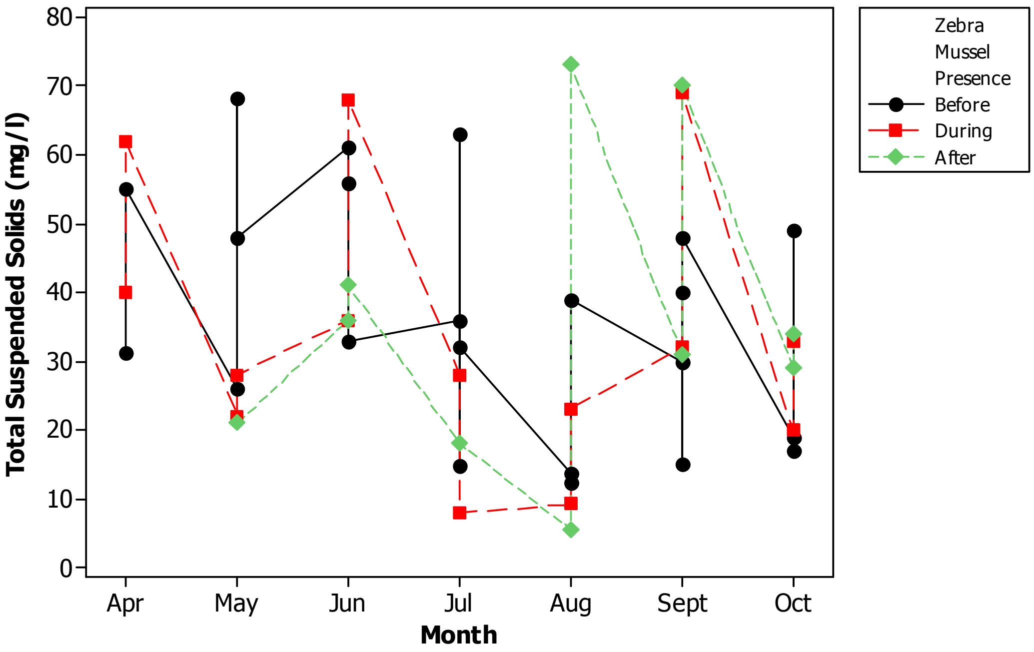

Figure 35. Scatterplot of total suspended solids (mg/l) for OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total suspended solid levels for OOL-5 sampling station ranged from 22.00 mg/l to 220.00 mg/l before zebra mussel arrival, and ranged from 16.00 mg/l to 160.00 mg/l during zebra mussel presence. After the die-off, the TSS levels ranged from 8.60 mg/l to 130.00 mg/l. Both the TSS concentration maximums and the means decreased over the treatment periods (Figures 36 and 37). There was no statistical significant difference (p=0.2560) between TSS treatment means at OOL-5 (Table 10).

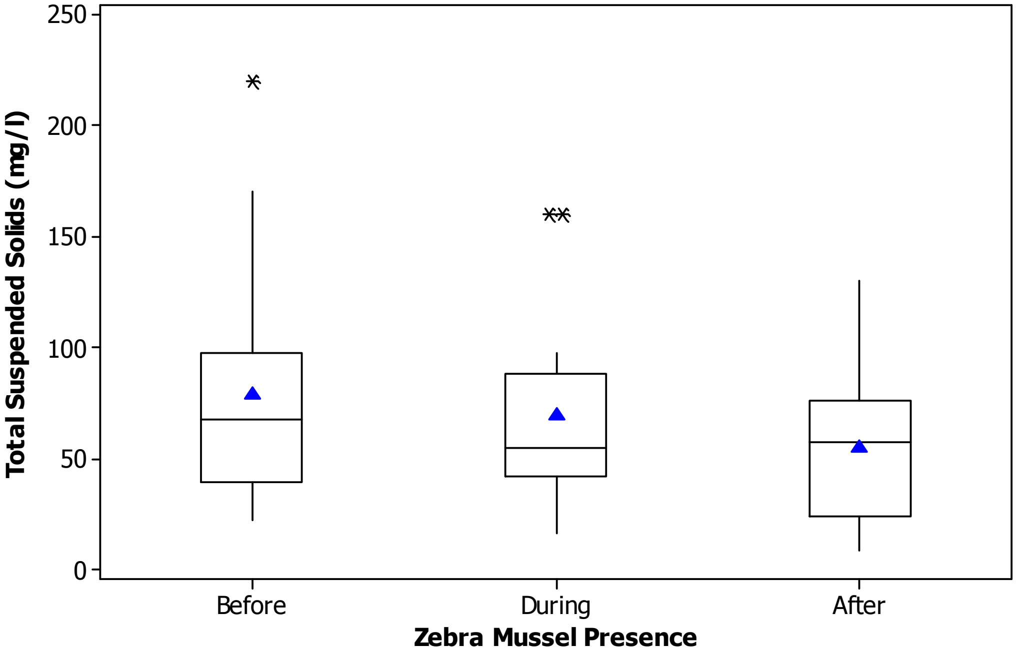

Figure 36. Boxplot of total suspended solids (mg/l) variability across OOL-5 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

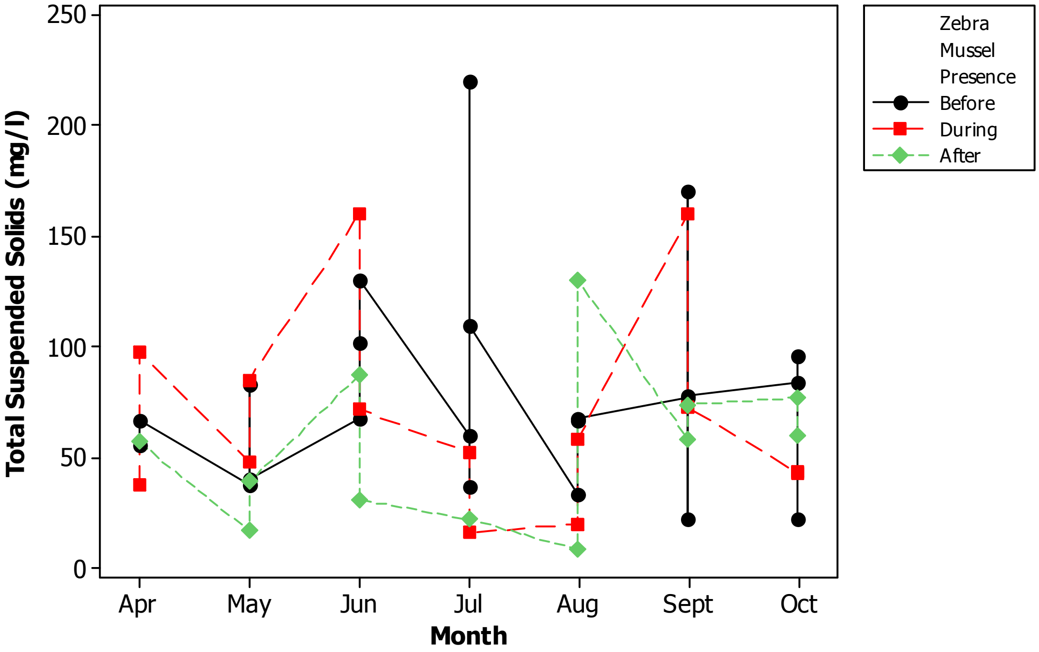

Figure 37. Scatterplot of total suspended solids (mg/l) for OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Table 5. Descriptive statistics for total suspended solids (mg/l) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	SE	Max	Min	Number of Obs.	Number of Obs. BDL[3]
Lake-wide						
Before	29.8873	3.29949	220.00	4.00	104	7
During	26.8500	3.83292	160.00	3.20	70	0
After	22.4698	3.19230	130.00	2.80	63	0
OOL-1						
Before	6.4968	0.6108	15.80	<4.00	16	6
During	5.5643	0.9647	17.00	3.20	14	0
After	5.3929	0.3433	8.00	2.80	14	0
OOL-2						
Before	10.8461	1.1077	24.00	<4.00	22	1
During	9.4571	1.0708	21.00	5.40	14	0
After	9.6929	1.1755	20.00	4.60	14	0
OOL-3						
Before	17.6818	1.7181	37.40	7.20	22	0
During	16.0000	2.9736	47.00	5.50	14	0
After	14.2462	1.9668	31.00	3.80	13	0
OOL-4						
Before	36.7000	3.7272	68.30	12.30	22	0
During	34.1571	5.2591	69.00	8.00	14	0
After	35.8600	6.7503	73.00	5.60	10	0
OOL-5						
Before	78.5773	10.1419	220.00	22.00	22	0
During	69.0714	11.9539	160.00	16.00	14	0
After	55.0500	9.9430	130.00	8.60	12	0

[1] April – October months used in analysis

[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008

[3] BDL=Below Detection Limit

As expected, the three water clarity parameters (Secchi, turbidity, and total suspended solids) values with the most notable differences between treatments correspond with each other. Where there was an increase in Secchi depth, there were decreases in turbidity and total suspended solids levels. Water clarity was most notably increased during the months of May through July during zebra mussel presence at OOL-1 (Figure 3, 17, and 29), during the months of April and May at OOL-2 (Figures 7, 19, and 31), during the months of April, May, and July at OOL-3 (Figures 9, 21, and 33), during the months of April through July at OOL-4 for Secchi and turbidity (Figures 13 and 23), and during the months of April and July at OOL-5 for Secchi and turbidity (Figures 13 and 25); for OOL-4 and OOL-5 the total suspended solids did correspond as strongly with the other water clarity parameters for the months listed (Figures 35 and 37).

Dissolved Oxygen

Zebra mussels have been reported to impact dissolved oxygen (DO) concentration levels both indirectly and directly, responding to water clarity impacts and increased rate of consumption due to zebra mussel population pressures. Descriptive statistics for DO concentration levels for lake-wide and the individual five sampling stations are presented in Table 6.

Lake-wide analysis of DO results from before zebra mussel invasion ranged from 5.49 mg/l to 12.67 mg/l; the results ranged from 5.12 mg/l to 10.81 mg/l in during zebra mussel presence. After the zebra mussel die-off the DO concentration levels ranged from 3.87 mg/l to 10.50 mg/l. Graphical summaries for the lake-wide DO results according to zebra mussel presence are presented in Figures 38 and 39. Lake-wide DO maximum results decreased after zebra mussel arrival and continued to decrease after their die-off; however, treatment means increased after zebra mussel arrival and decreased after the die-off. There was no significant difference (p=0.0856) among the treatment (*Before*, *During*, and *After*) means in the lake-wide analysis (Table 10).

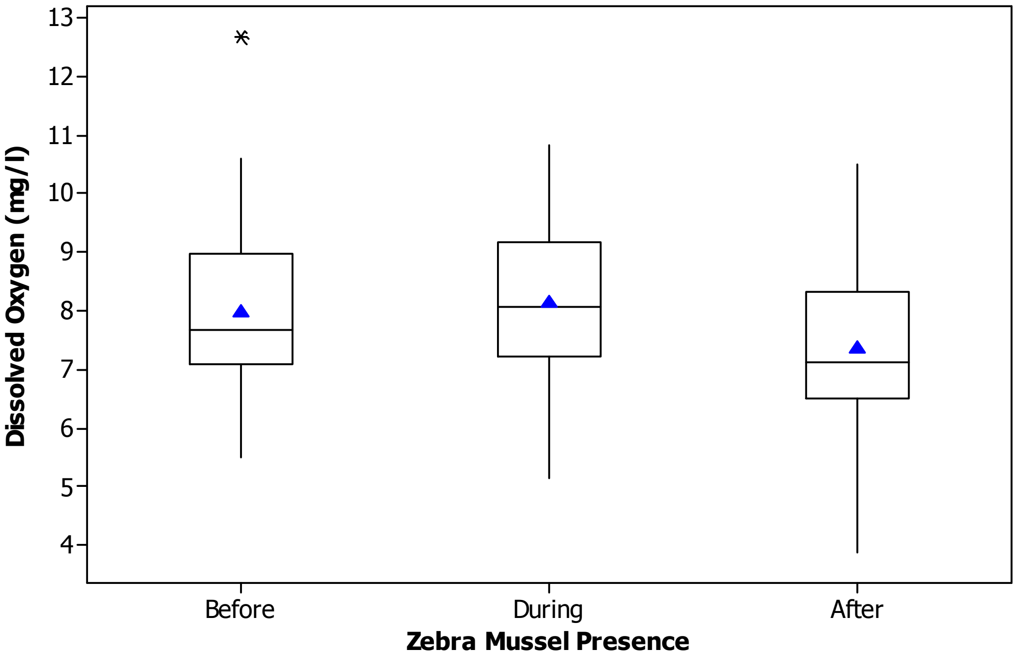

Figure 38. Boxplot of dissolved oxygen (mg/l) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

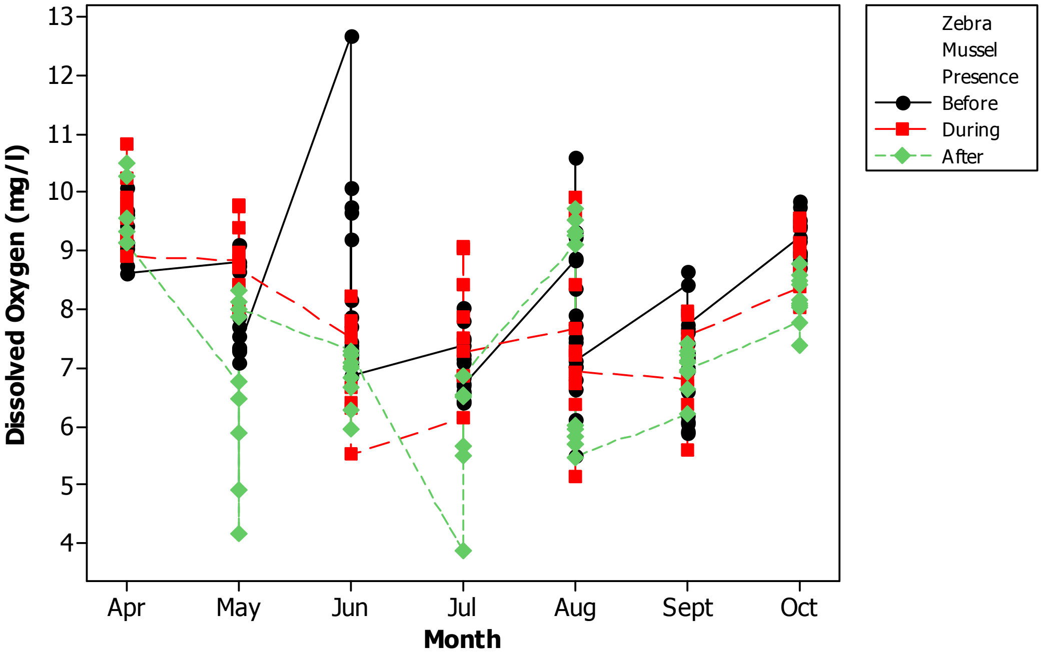

Figure 39. Scatterplot of dissolved oxygen (mg/l) for all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Dissolved oxygen concentration levels for OOL-1 sampling station ranged from 5.49 mg/l to 12.67 mg/l before zebra mussel arrival, and ranged from 5.12 mg/l to 9.90 mg/l during zebra mussel presence. After the die-off, the DO concentration levels ranged from 3.87 mg/l to 10.50 mg/l. The maximum and mean DO concentration levels decrease after zebra mussel arrival (Figures 40 and 41); the mean concentration decreased after the die-off (Figure 40). There was no statistical significant difference (p=0.3067) between DO treatment means at OOL-1 (Table 10).

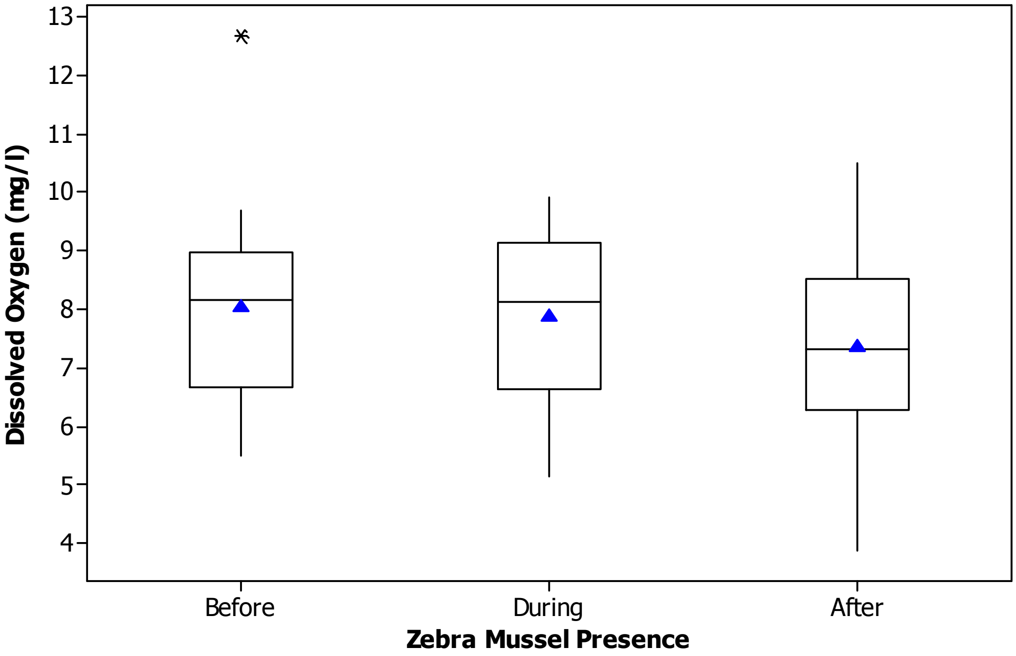

Figure 40. Boxplot of dissolved oxygen (mg/l) variability across OOL-1 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

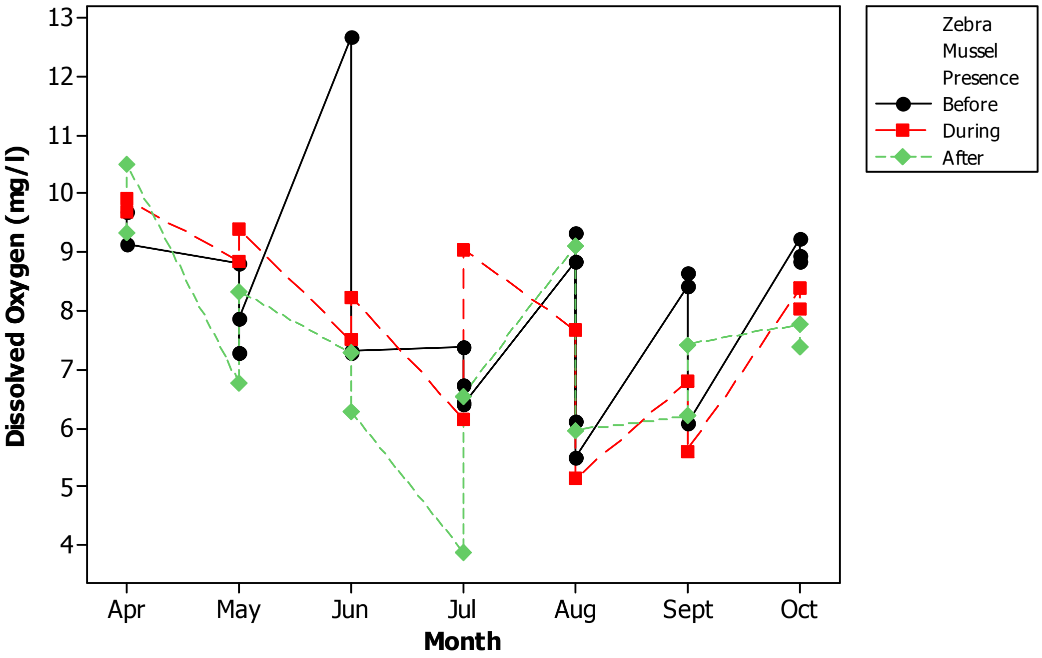

Figure 41. Scatterplot of dissolved oxygen (mg/l) for OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Dissolved oxygen concentration levels for OOL-2 sampling station ranged from 5.90 mg/l to 10.07 mg/l before zebra mussel arrival, and ranged from 6.36 mg/l to 9.92 mg/l during zebra mussel presence. After the die-off, the DO levels ranged from 5.64 mg/l to 10.28 mg/l. Mean DO concentration values increased after zebra mussel arrival and decreased after the die-off (Figures 42 and 43). There was no statistical significant difference (p=0.0728) between DO treatment means at OOL-2 (Table 10).

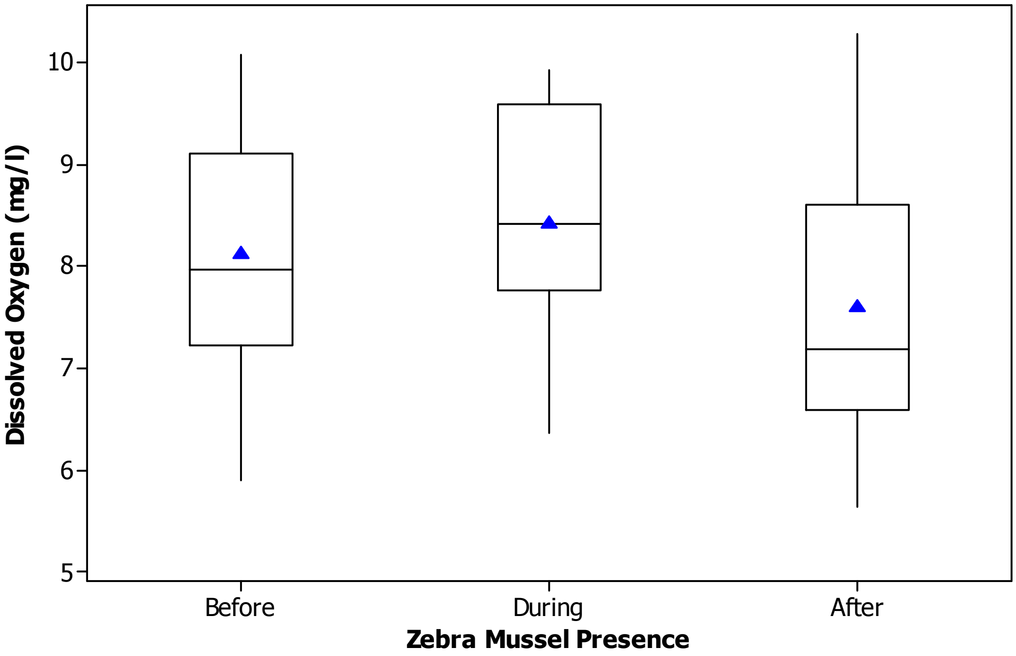

Figure 42. Boxplot of dissolved oxygen (mg/l) variability across OOL-2 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

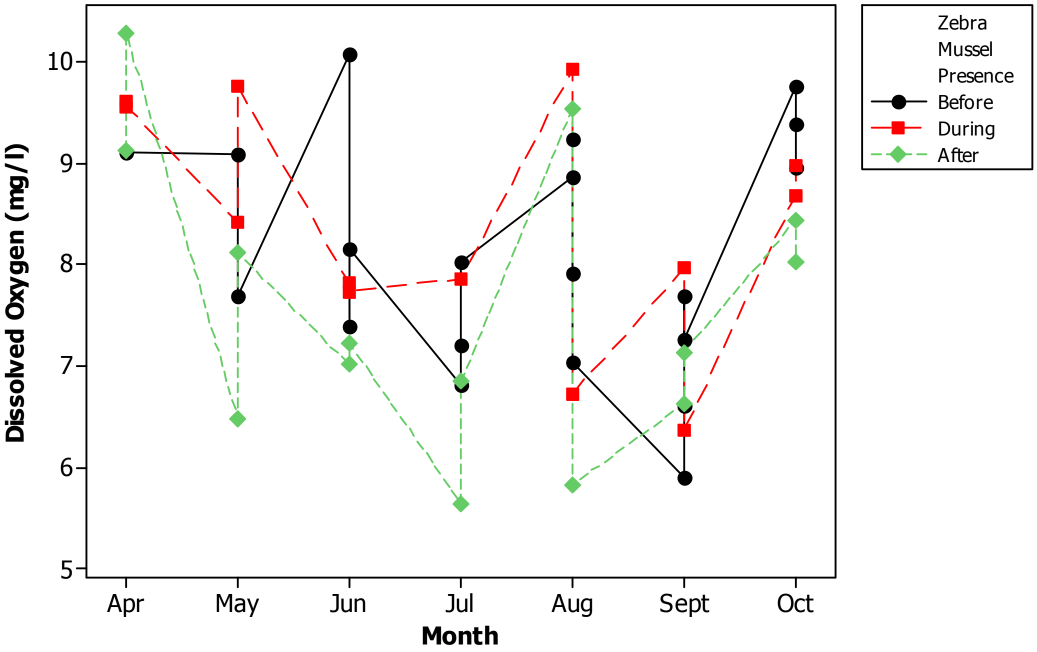

Figure 43. Scatterplot of dissolved oxygen (mg/l) for OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Dissolved oxygen concentration levels for OOL-3 sampling station ranged from 5.89 mg/l to 9.44 mg/l before zebra mussel arrival, and ranged from 6.66 mg/l to 9.82 mg/l during zebra mussel presence. After the die-off, the DO levels ranged from 4.89 mg/l to 9.71 mg/l. Like the lake-wide and OOL -2 results, DO concentration means increased during zebra mussel presence (Figures 44 and 45). However, the difference in treatment DO concentration means was statistically significant (p=0.0409) at OOL-3 (Table 10). Post Hoc comparison shows the *During* and *After* treatment means are significantly different (p=0.0124); however the *Before* treatment mean was not significantly different from the *During* or *After* means (p=0.2482 and p=0.1085, respectively) (Table 10).

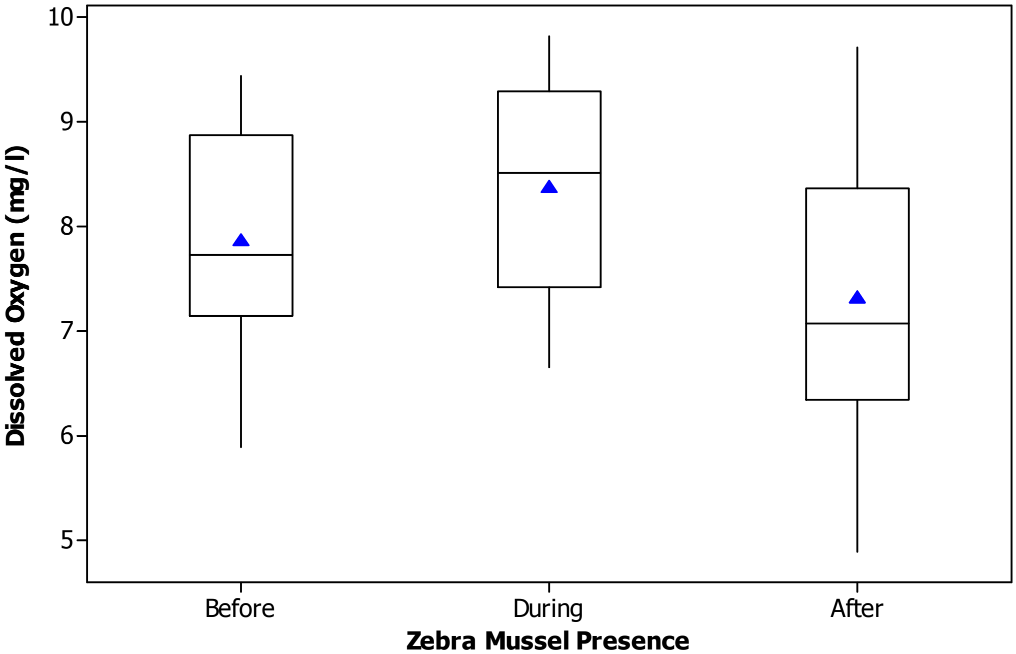

Figure 44. Boxplot of dissolved oxygen (mg/l) variability across OOL-3 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

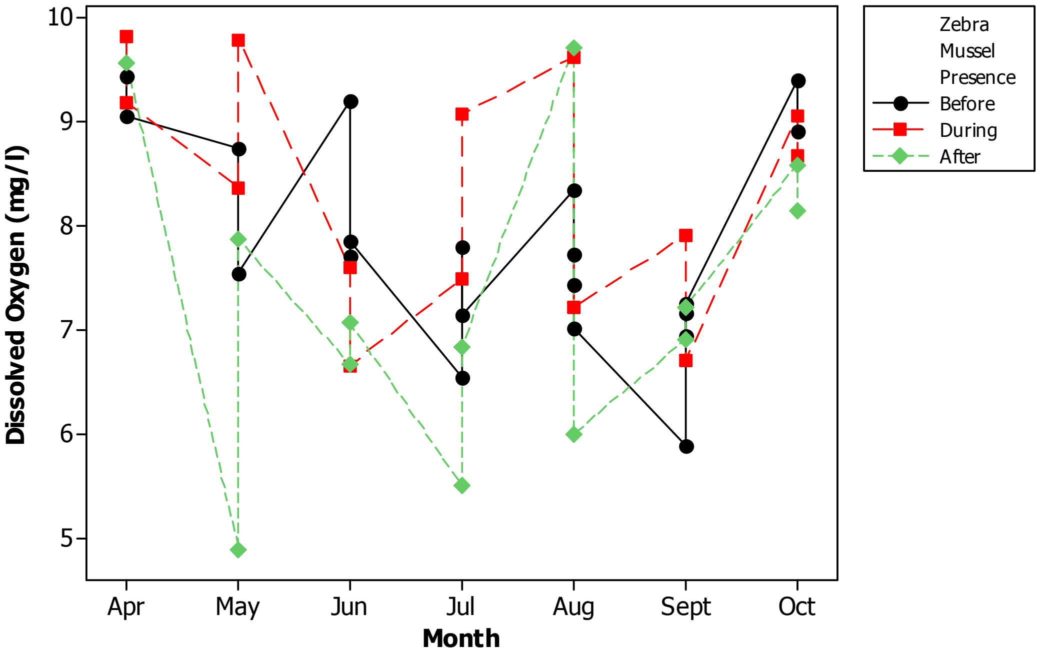

Figure 45. Scatterplot of dissolved oxygen (mg/l) for OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Dissolved oxygen concentration levels for OOL-4 sampling station ranged from 6.04 mg/l to 10.58 mg/l before zebra mussel arrival, and ranged from 6.38 mg/l to 10.23 mg/l during zebra mussel presence. After the die-off, the DO levels ranged from 4.16 mg/l to 9.25 mg/l. The mean DO concentration level during zebra mussel presence increased and then decreased after the die-off (Figures 46 and 47). However, there was no statistical significant difference (p=0.1292) between DO treatment means at OOL-4 (Table 10).

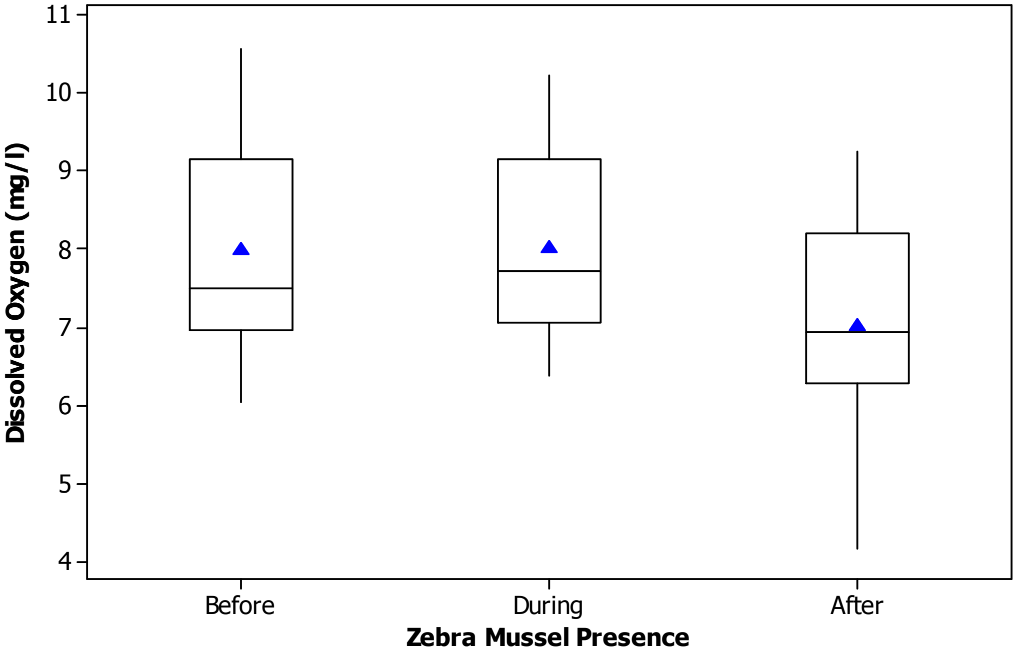

Figure 46. Boxplot of dissolved oxygen (mg/l) variability across OOL-4 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

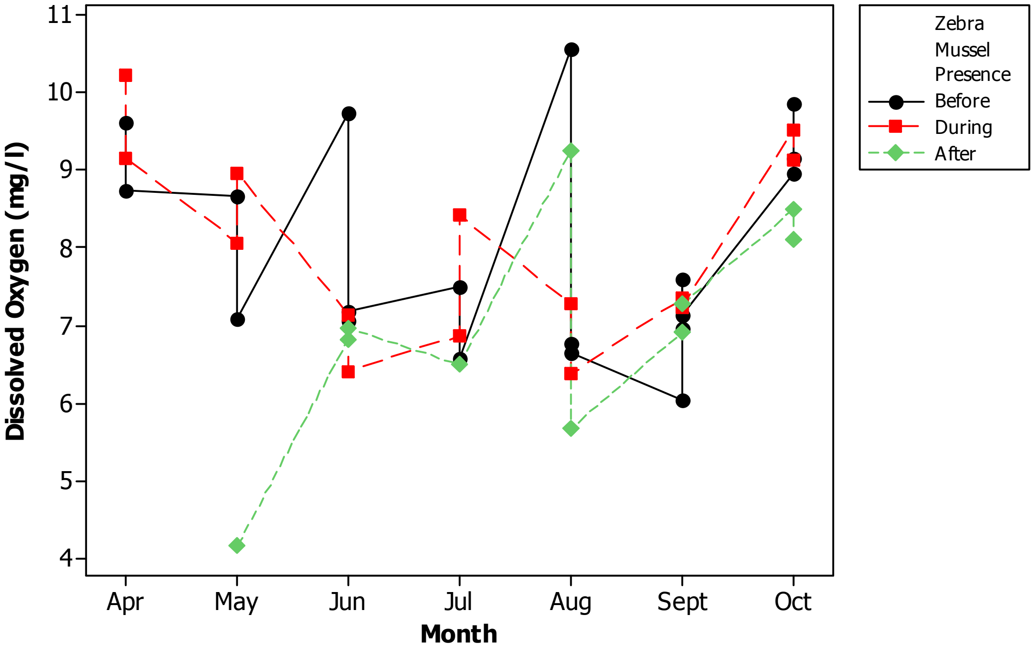

Figure 47. Scatterplot of dissolved oxygen (mg/l) for OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Dissolved oxygen concentration levels for OOL-5 sampling station ranged from 6.18 mg/l to 10.08 mg/l before zebra mussel arrival and ranged from 5.51 mg/l to 10.81 mg/l during zebra mussel presence. After the die-off, the DO concentration levels ranged from 5.47 mg/l to 9.32 mg/l. As observed at OOL-4, the mean DO concentration level increased after the zebra mussel arrival and decreased after the die-off (Figures 48 and 49). There was no statistical significant difference (p=0.3220) between DO treatment means at OOL-5 (Table 10).

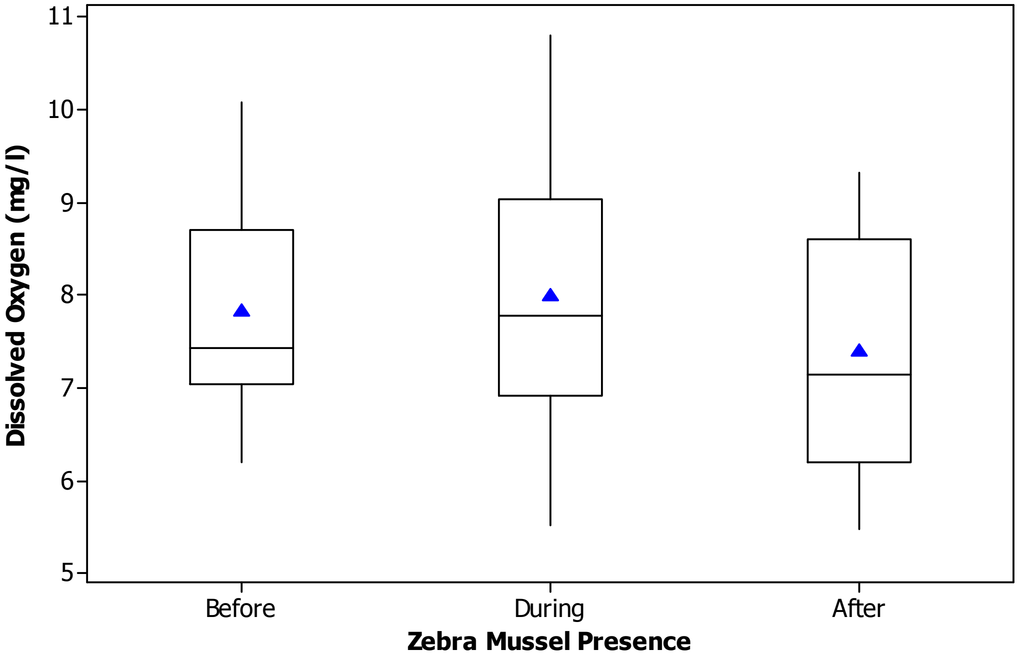

Figure 48. Boxplot of dissolved oxygen (mg/l) variability across OOL-5 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

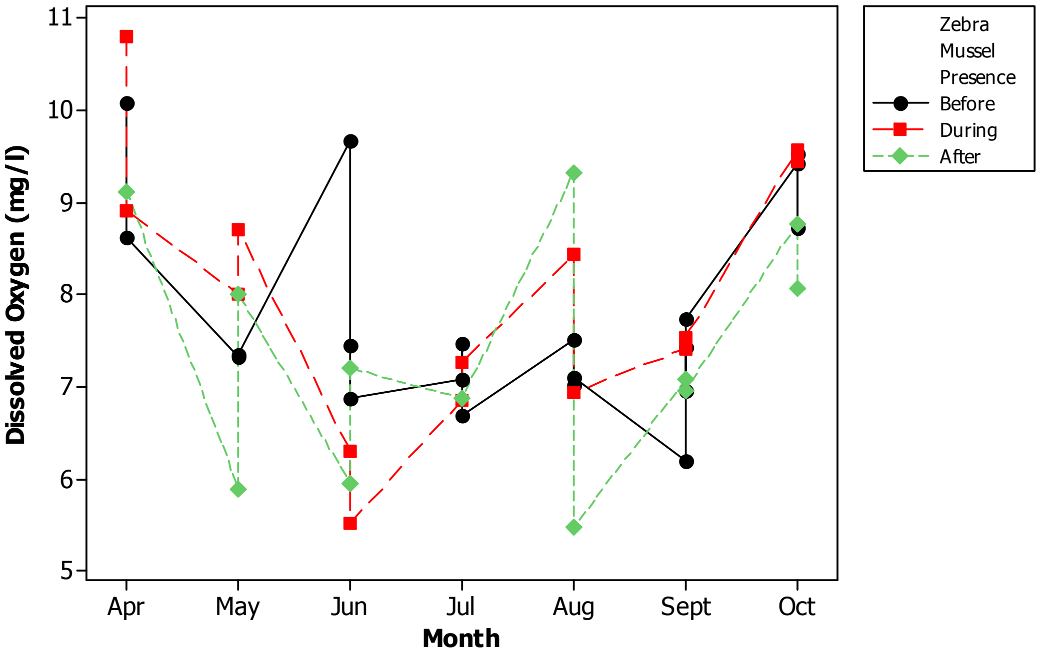

Figure 49. Scatterplot of dissolved oxygen (mg/l) for OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

ANCOVA p-values resulted in only one station, OOL-3, having a significant difference between the means. At most stations (OOL-1 as the exception) the mean DO concentration levels increased after the zebra mussel arrival (*During* treatment) and decreased after the zebra mussel die-off (*After* treatment) (Figures 38, 40, 42, 44, 46, and 48). Across all stations, the lowest DO concentrations recorded were observed during the *After* treatment period (Table 6). These lowest values were reported in June and July at OOL-1 (Figure 41); in May, July, and August at OOL-2 and OOL-3 (Figures 43 and 45); and in May and August for OOL-4 and OOL-5 (Figures 47 and 49).

Table 6. Descriptive statistics for dissolved oxygen (mg/l) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	SE	Max	Min	Number of Obs.	Number of Obs. BDL[3]
Lake-wide						
Before	7.96297	0.12461	12.67	5.49	101	0
During	8.12493	0.15355	10.81	5.12	69	0
After	7.34556	0.17850	10.50	3.87	63	0
OOL-1						
Before	8.04227	0.34406	12.67	5.49	22	0
During	7.87714	0.40217	9.90	5.12	14	0
After	7.33500	0.44248	10.50	3.87	14	0
OOL-2						
Before	8.10600	0.25760	10.07	5.90	20	0
During	8.41077	0.31643	9.92	6.36	13	0
After	7.59071	0.36991	10.28	5.64	14	0
OOL-3						
Before	7.85800	0.22418	9.44	5.89	20	0
During	8.37000	0.29669	9.82	6.66	14	0
After	7.30538	0.40181	9.71	4.89	13	0
OOL-4						
Before	7.99474	0.30972	10.58	6.04	19	0
During	8.01214	0.32915	10.23	6.38	14	0
After	7.01500	0.45565	9.25	4.16	10	0
OOL-5						
Before	7.80750	0.24997	10.08	6.18	20	0
During	7.97500	0.38209	10.81	5.51	14	0
After	7.39083	0.36989	9.32	5.47	12	0

[1] April – October months used in analysis
[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008
[3] BDL=Below Detection Limit

Total Ammonia

Zebra mussels have been reported to impact total ammonia concentration levels both indirectly and directly, responding to both filtering impacts and excretion due to zebra mussel population pressures. Descriptive statistics for ammonia concentration levels for lake-wide and the individual five sampling stations are presented in Table 7. It is important to note that the lab performing the ammonia analysis used different detection limits within the 2000 – 2008 study period, as noted in Table 2; in 2007 and 2008, the detection limit was higher (set at 0.10 mg/l). For 2007 and 2008 all results were below the detection limit, except for OOL-4 and OOL-5 during the August sampling trip for both years (Appendix 2). The detection limit was used as the concentration level for ANCOVA purposes.

Before zebra mussel presence, Lake-wide analysis of ammonia results ranged from below the detection limit (<0.023 mg/l) to 0.520 mg/l; the results ranged from below the detection limit (<0.023 mg/l) to 0.100 mg/l during zebra mussel presence. After the zebra mussel die-off, ammonia concentration levels ranged from below the detection limit (<0.010 mg/l) to 0.140 mg/l. Graphical summaries for the lake-wide results according to zebra mussel presence are presented in Figures 50 and 51. Lake-wide ammonia mean and maximum concentration levels decreased after zebra mussel arrival and increased after the die-off. There was a significant difference (p=0.0166) among the *Before*, *During*, and *After* treatment means (Table 10). Post Hoc comparison shows the *During* treatment mean was significantly different from the *Before* and *After* treatment means (p=0.0284 and p=0.0048, respectively) (Table 10). However, the *Before* and *After* treatment means were not significantly different (p=0.1266) (Table 10).

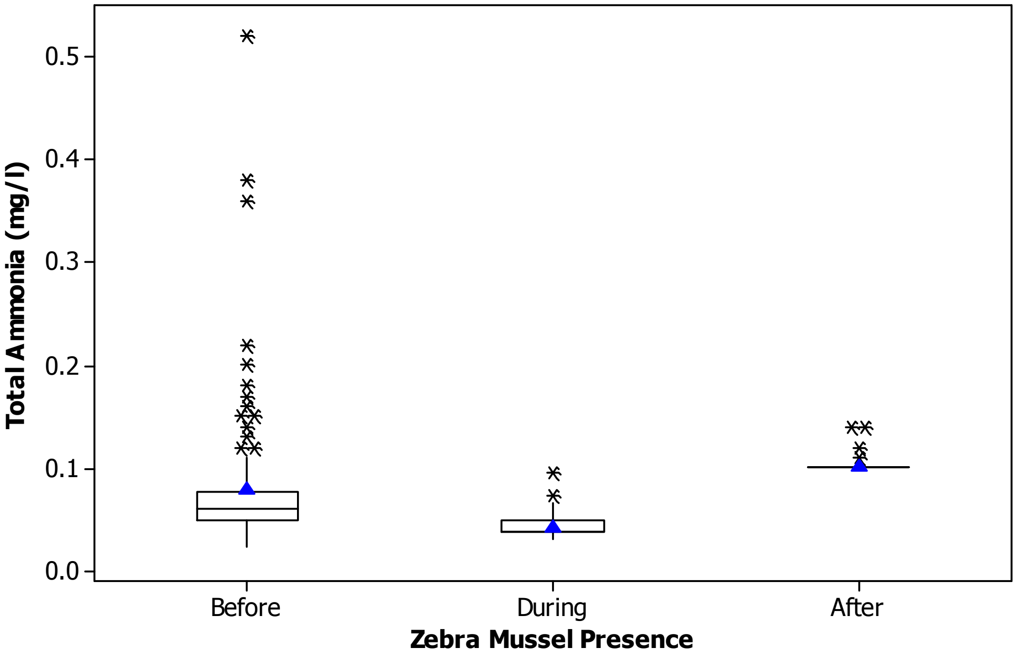

Figure 50. Boxplot of total ammonia (mg/l) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

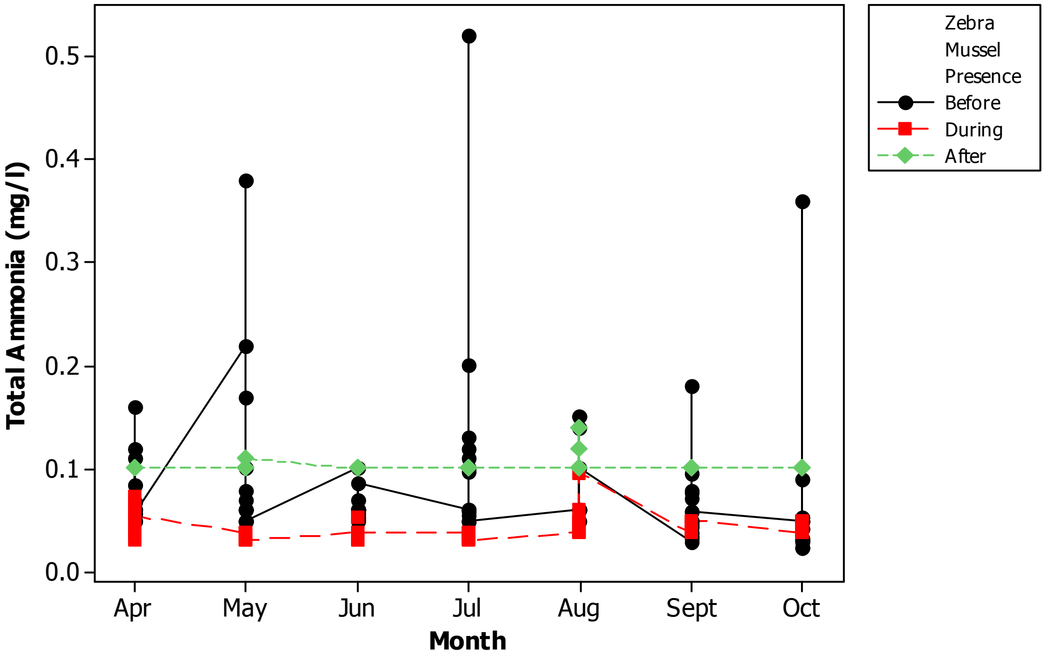

Figure 51. Scatterplot of total ammonia (mg/l) for all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total ammonia concentration levels for OOL-1 sampling station ranged from below the detection limit (<0.030 mg/l) to 0.520 mg/l before zebra mussel arrival and ranged from below the detection limit (<0.030 mg/l) to 0.050 mg/l during zebra mussel presence. After the die-off, the ammonia concentration levels remained below the detection limit of <0.100 mg/l. The maximum and mean ammonia concentration levels decreased after zebra mussel arrival and increased after the die-off (Figures 52 and 53). There was a significant difference (p=0.0493) among the *Before*, *During*, and *After* treatment means (Table 10). Post Hoc comparison shows the *During* treatment mean was significantly different from the *Before* and *After* treatment means (p=0.0324 and p=0.0290, respectively) (Table 10). However, the *Before* and *After* treatment means were not significantly different (p=0.7937) (Table 10).

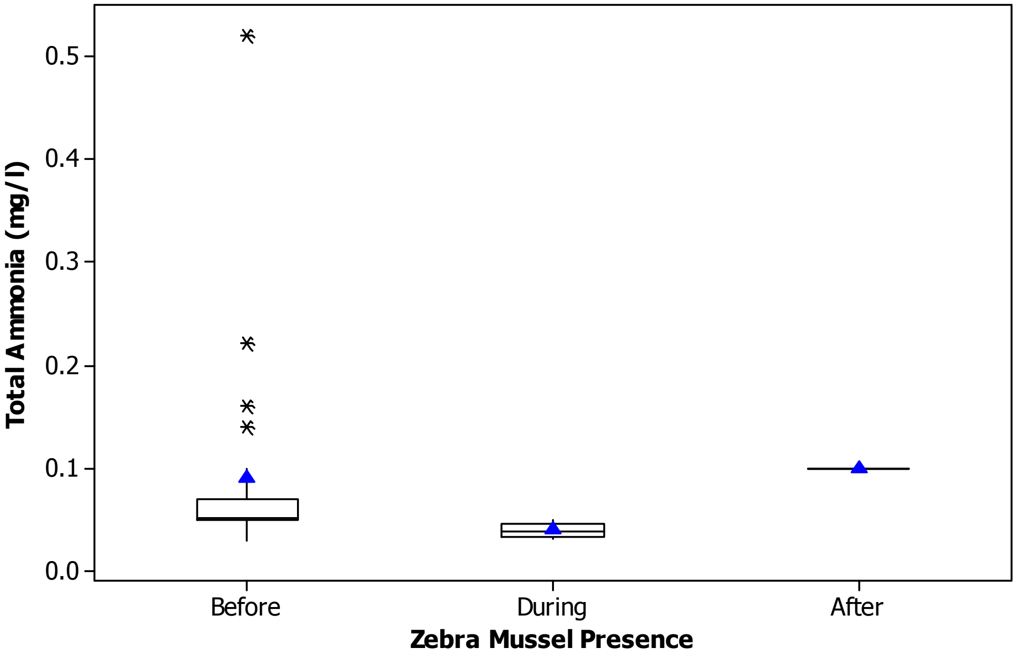

Figure 52. Boxplot of total ammonia (mg/l) variability across OOL-1 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

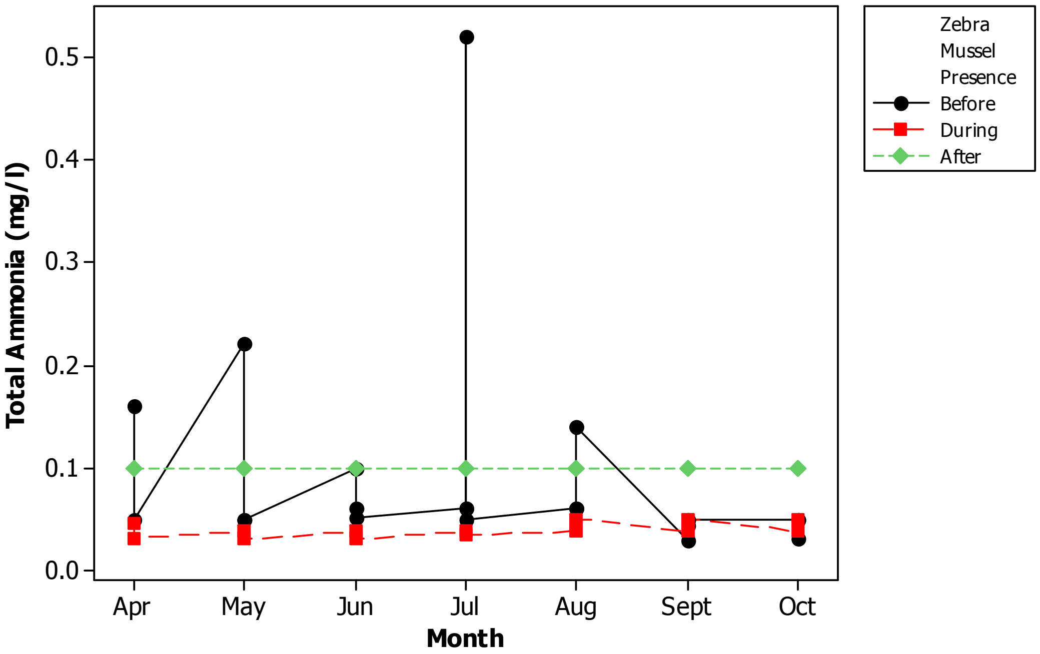

Figure 53. Scatterplot of total ammonia (mg/l) for OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total ammonia concentration levels for OOL-2 sampling station ranged from below the detection limit (<0.023 mg/l) to 0.12 mg/l before zebra mussel arrival and ranged from below the detection limit (<0.030 mg/l) to 0.063 mg/l during zebra mussel presence. After the die-off, the ammonia levels at OOL-2 remained below the detection limit of <0.10 mg/l. Like OOL-1, the maximum and mean ammonia concentration levels decreased after zebra mussel arrival and increased again after the die-off at OOL-2 (Figures 54 and 55). There was a significant difference (p=<0.0001) among the *Before*, *During*, and *After* treatment means (Table 10). Post Hoc comparisons resulted in all the treatment means being significantly different from one another (Table 10). .

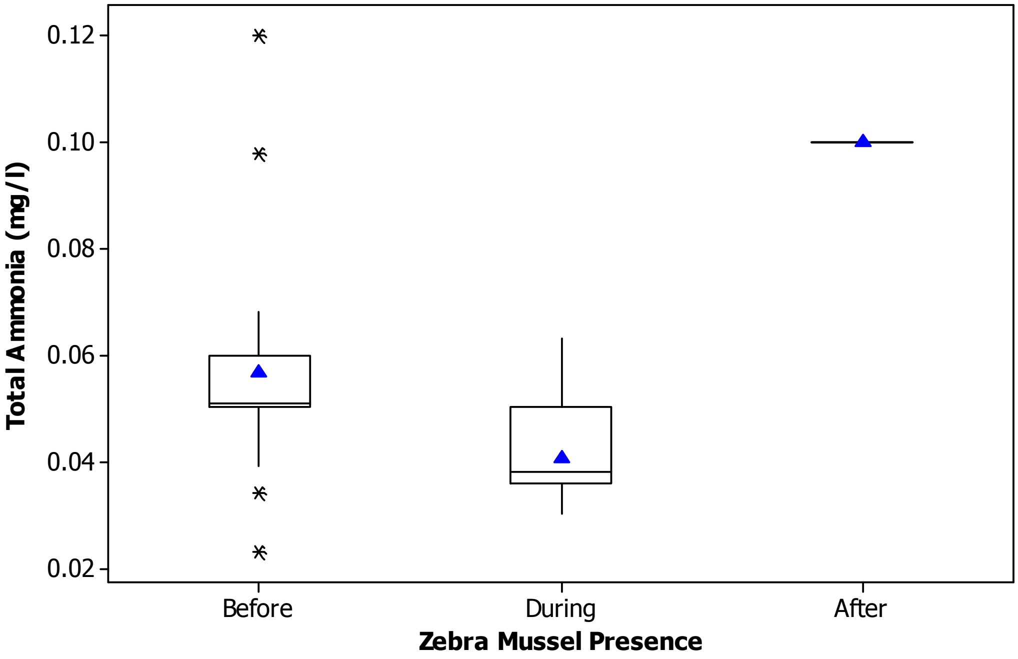

Figure 54. Boxplot of total ammonia (mg/l) variability across OOL-2 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

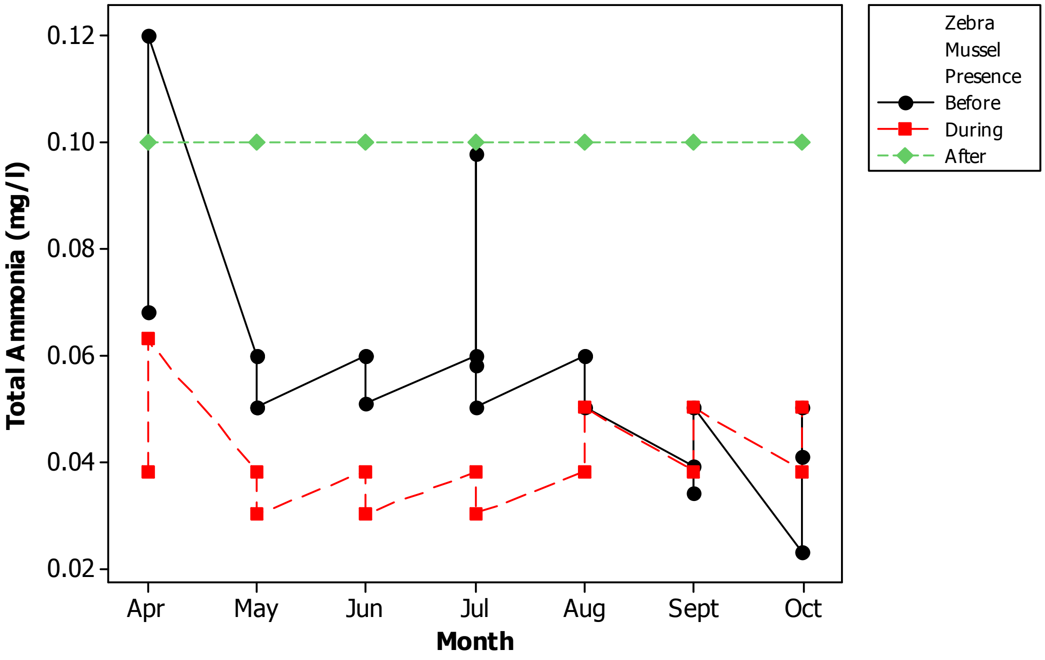

Figure 55. Scatterplot of total ammonia (mg/l) for OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total ammonia concentration levels for OOL-3 sampling station ranged from below the detection limit (<0.050 mg/l) to 0.150 mg/l before zebra mussel arrival and ranged from below the detection limit (<0.030 mg/l) to 0.070 mg/l during zebra mussel presence. After the die-off, the ammonia levels remained below the detection limit of <0.10 mg/l. As seen at the previous sites, the maximum and mean ammonia concentration levels decreased after zebra mussel arrival and increased after the die-off (Figures 56 and 57). There was a significant difference (p=<0.0001) among the *Before*, *During*, and *After* treatment means (Table 10). Post Hoc comparisons resulted in all the treatment means being significantly different from one another (Table 10).

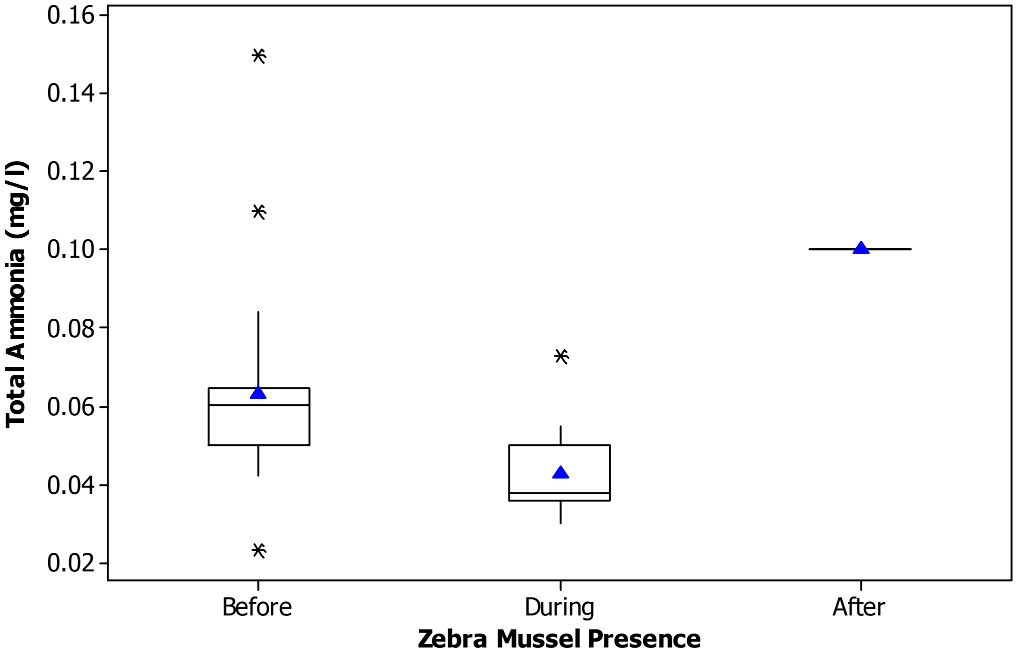

Figure 56. Boxplot of total ammonia (mg/l) variability across OOL-3 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

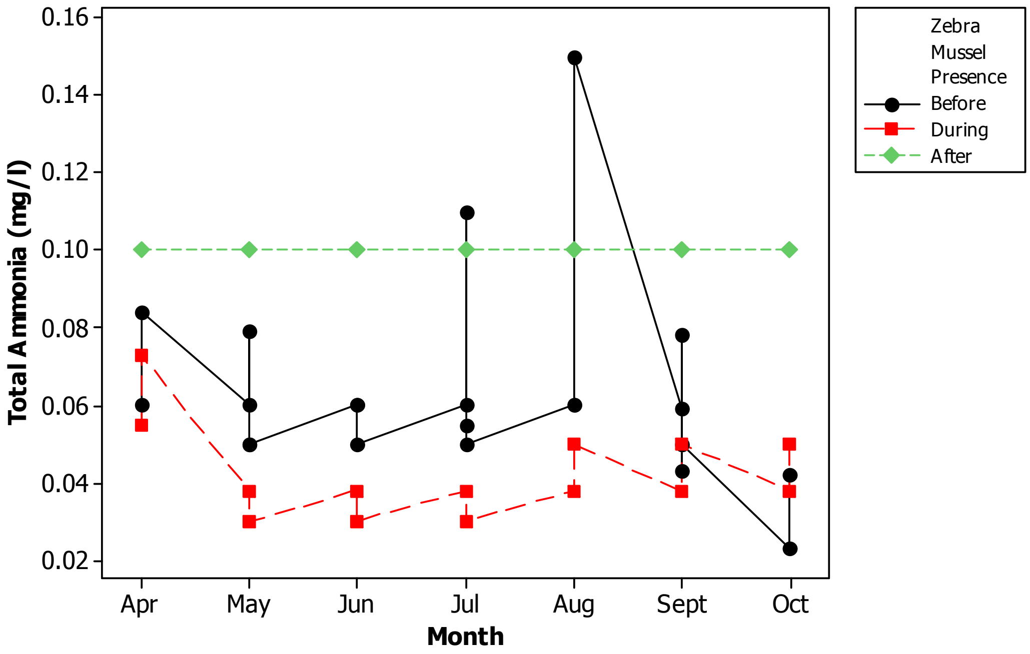

Figure 57. Scatterplot of total ammonia (mg/l) for OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total ammonia concentration levels for OOL-4 sampling station ranged from below the detection limit (<0.050 mg/l) to 0.380 mg/l before zebra mussel arrival and ranged from below the detection limit (<0.030 mg/l) to 0.070 mg/l during zebra mussel presence. After the die-off, the ammonia levels ranged from below the detection limit (<0.10 mg/l) to 0.140 mg/l. Although the maximum and mean ammonia concentration levels decreased after zebra mussel arrival and increased after the die-off (Figures 58 and 59), there was no significant difference (p=0.1092) between the treatment means at OOL-4 (Table 10).

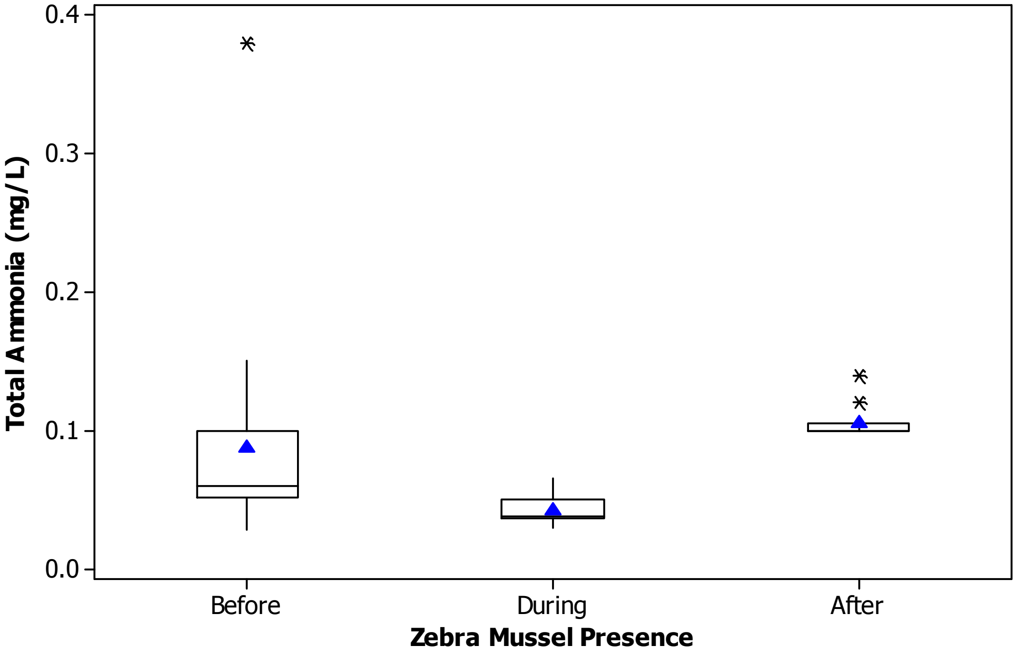

Figure 58. Boxplot of total ammonia (mg/l) variability across OOL-4 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

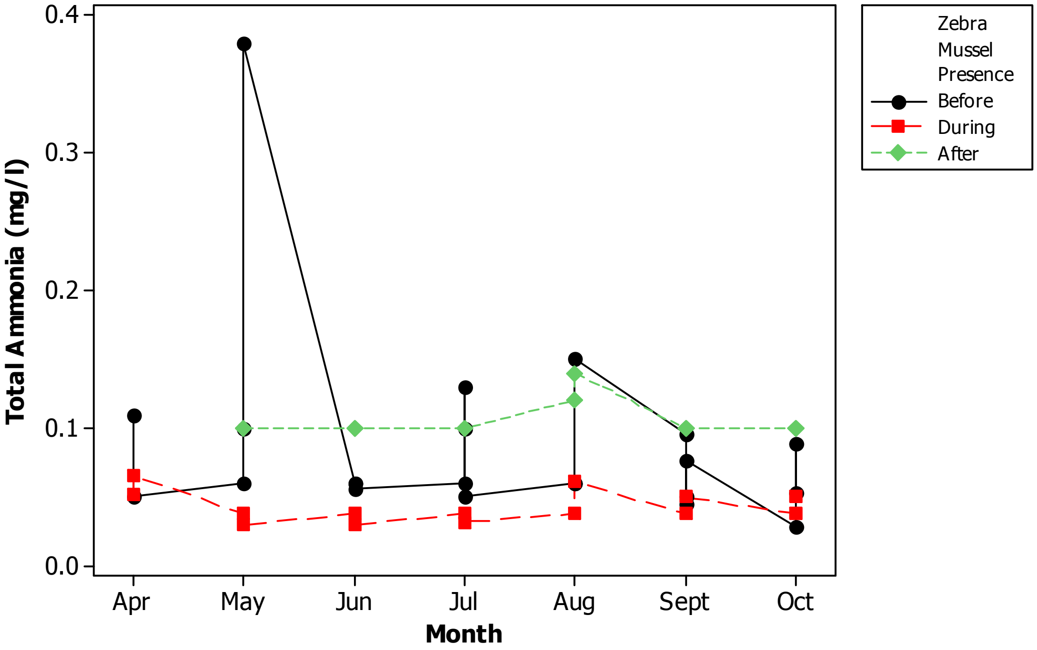

Figure 59. Scatterplot of total ammonia (mg/l) for OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total ammonia concentration levels for OOL-5 sampling station ranged from below the detection limit (<0.030 mg/l) to 0.360 mg/l before zebra mussel arrival and ranged from below the detection limit (<0.030 mg/l) to 0.096 mg/l during zebra mussel presence. After the die-off, the ammonia levels ranged from below the detection limit (<0.10 mg/l) to 0.140 mg/l. As seen at OOL-4, the maximum and mean ammonia concentration levels at OOL-5 decreased after zebra mussel arrival and increased after the die-off (Figures 60 and 61); however, there was no significant difference (p=0.1092) between the treatment means at OOL-5 (Table 10).

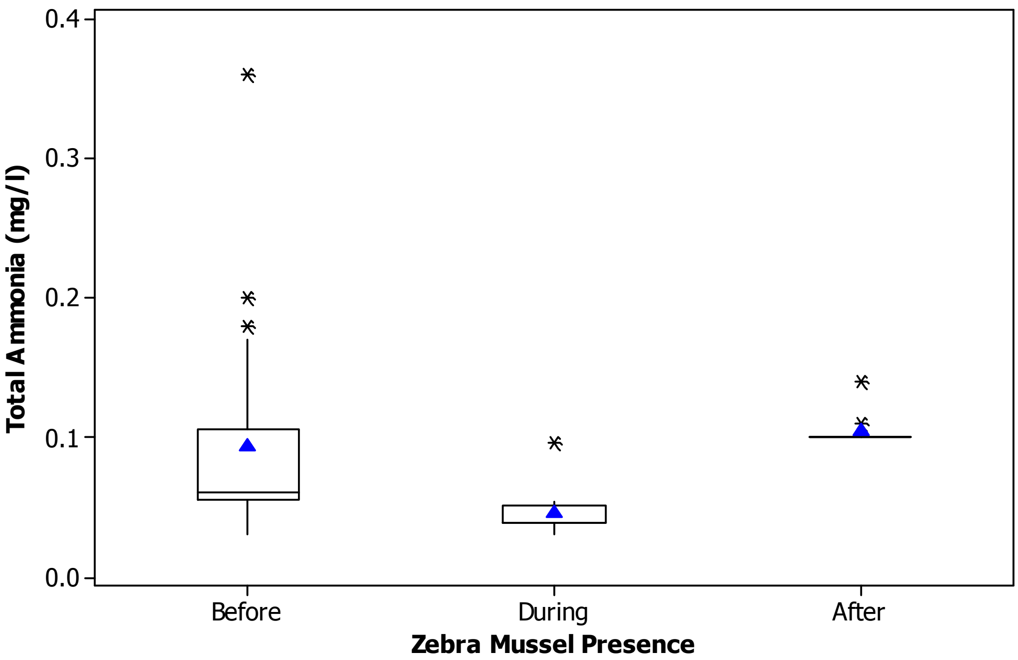

Figure 60. Boxplot of total ammonia (mg/l) variability across OOL-5 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

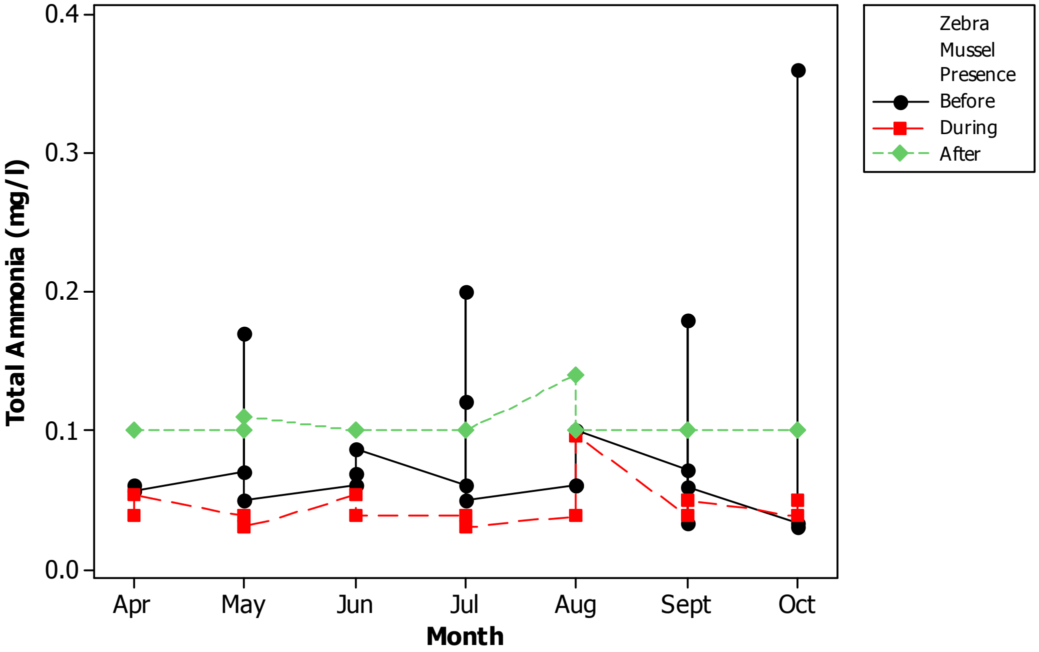

Figure 61. Scatterplot of total ammonia (mg/l) for OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

The ANCOVA p-value results indicate significance in the difference between treatment means at OOL-1, OOL-2, and OOL-3; the ammonia concentrations at these sites were significantly lower during zebra mussel presence (Figures 52, 54, and 56). Across all stations, the variability in total ammonia concentrations was greatest prior to zebra mussel arrival (Figures 50 through 61).

Table 7. Descriptive statistics for total ammonia (mg/l) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	**SE**	**Max**	**Min**	**Number of Obs.**	**Number of Obs. BDL[3]**
Lake-wide						
Before	0.07792	0.006498638	0.520	<0.023	53	58
During	0.04203	0.001376221	0.100	<0.023	14	56
After	0.10175	0.000947676	0.140	<0.100	4	59
OOL-1						
Before	0.09059	0.022680	0.520	<0.030	9	13
During	0.03914	0.001898	0.050	<0.030	3	11
After	0.10000	0.000000	<0.100	<0.100	0	14
OOL-2						
Before	0.05661	0.004093	0.120	<0.023	8	15
During	0.04064	0.002515	0.063	<0.030	1	13
After	0.10000	0.000000	<0.100	<0.100	0	14
OOL-3						
Before	0.06332	0.005530	0.150	<0.050	9	13
During	0.04257	0.003184	0.070	<0.030	2	12
After	0.10000	0.000000	<0.100	<0.100	0	13
OOL-4						
Before	0.08741	0.015330	0.380	<0.050	13	9
During	0.04279	0.003002	0.070	<0.030	4	10
After	0.10600	0.004269	0.140	<0.100	2	8
OOL-5						
Before	0.09264	0.016211	0.360	<0.030	14	8
During	0.04500	0.004433	0.096	<0.030	4	10
After	0.10417	0.003362	0.140	<0.100	2	10

[1] April – October months used in analysis

[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008

[3] BDL=Below Detection Limit

Total Phosphorus

As with total ammonia, zebra mussels have been reported to impact total phosphorus concentration levels by responding to both filtering impacts and excretion due to zebra mussel population pressures. Descriptive statistics for phosphorus concentration levels for lake-wide and the five sampling stations are presented in Table 8.

Before zebra mussel presence, lake-wide analysis of phosphorus results ranged from below the detection limit (<0.020 mg/l) to 0.500 mg/l; the results ranged from 0.020 mg/l to 0.440 mg/l during zebra mussel presence. After the zebra mussel die-off phosphorus concentration levels ranged from 0.030 mg/l to 0.330 mg/l. Graphical summaries for the lake-wide results according to zebra mussel presence are presented in Figures 62 and 63. While the lake-wide phosphorus maximum concentration levels decreased after zebra mussel arrival, the treatment mean values slightly increased. There was no significant difference (p=0.8294) between treatment means for the lake-wide analysis of phosphorus concentration levels (Table 10).

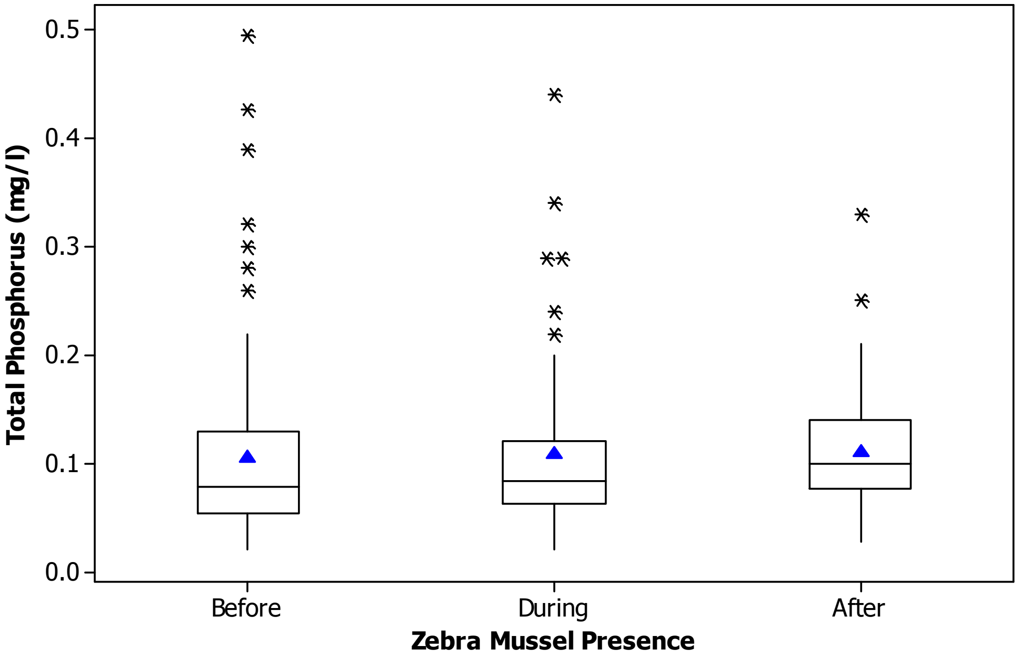

Figure 62. Boxplot of total phosphorus (mg/l) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

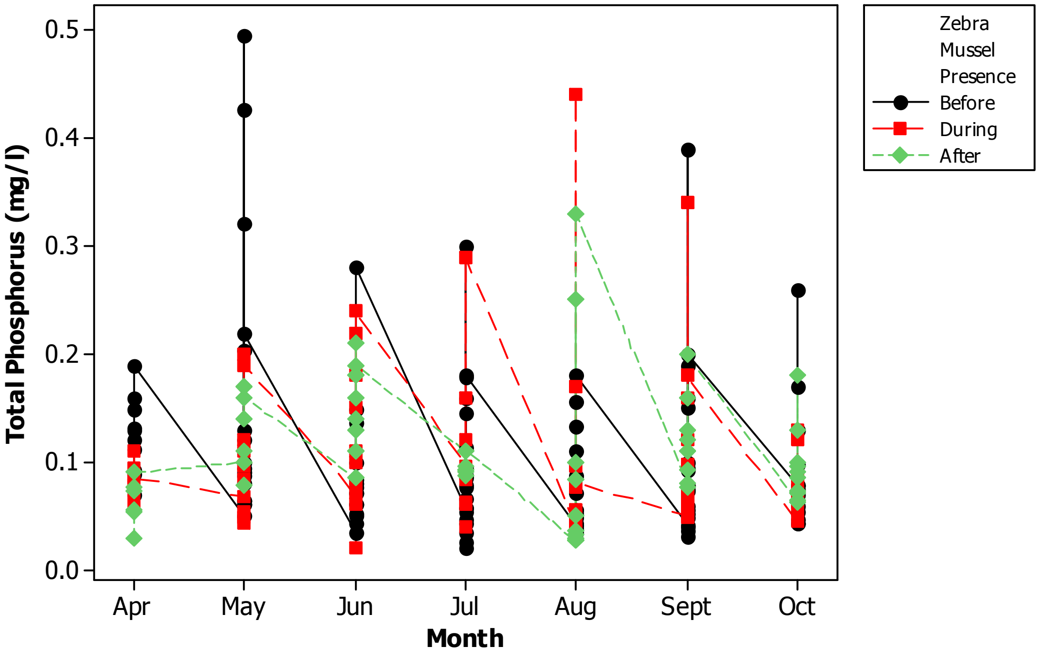

Figure 63. Scatterplot of total phosphorus (mg/l) for all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total phosphorus concentration levels for OOL-1 sampling station ranged from 0.020 mg/l to 0.095 mg/l before zebra mussel arrival and ranged from 0.020 mg/l to 0.096 mg/l during zebra mussel presence. After the die-off, the phosphorus concentration levels ranged from 0.027 mg/l to 0.130 mg/l. The maximum and mean phosphorus concentration levels increased after zebra mussel arrival and continued to increase after the die-off (Figures 64 and 65). There was a significant difference (p=0.0436) among the *Before*, *During*, and *After* treatment means (Table 10). Post Hoc comparison showed the *Before* treatment mean is significantly different from the *After* treatment mean (p=0.0134) (Table 10). However, the *During*/*Before* and *During*/*After* treatment means were not significantly different (p=0.4627 and p=0.1014, respectively) (Table 10).

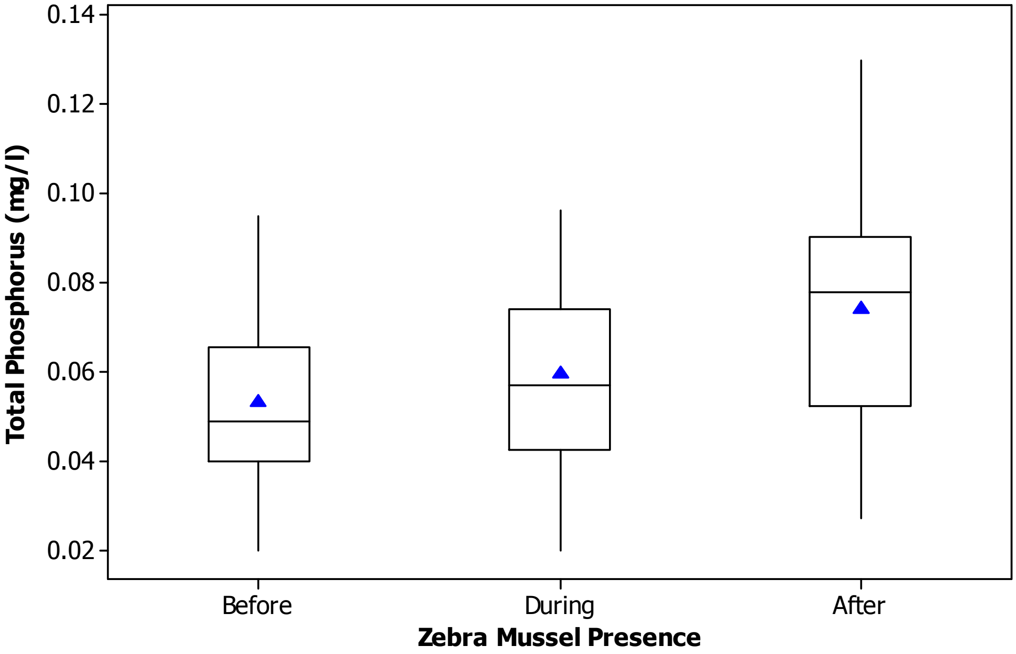

Figure 64. Boxplot of total phosphorus (mg/l) variability across OOL-1 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

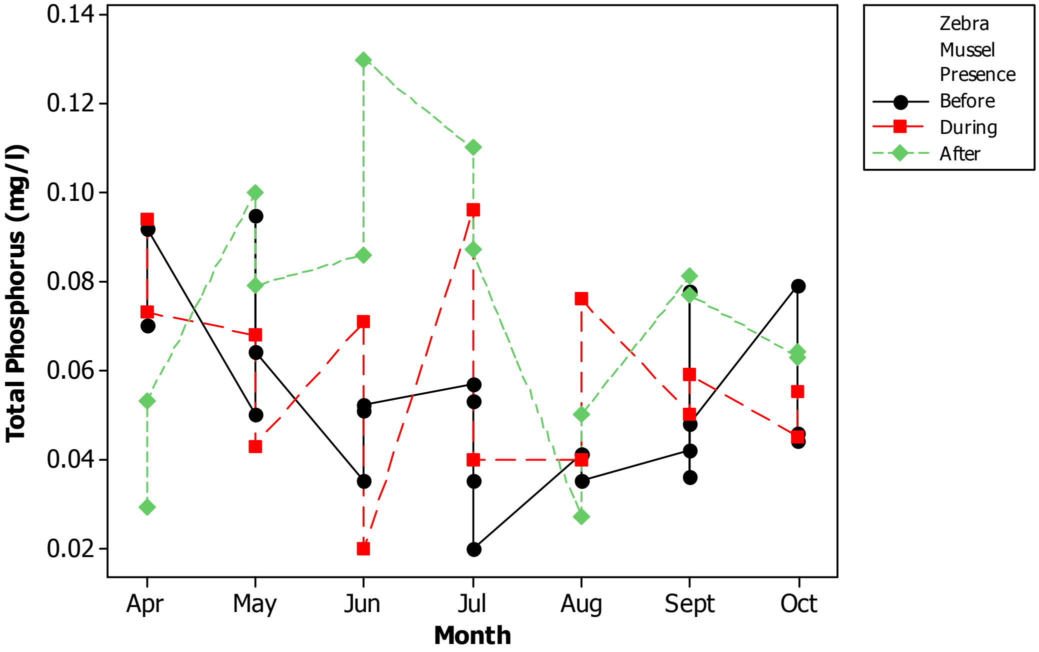

Figure 65. Scatterplot of total phosphorus (mg/l) for OOL-1 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total phosphorus concentration levels for OOL-2 sampling station ranged from 0.025 mg/l to 0.427 mg/l before zebra mussel arrival and ranged from 0.040 mg/l to 0.440 mg/l during zebra mussel presence. After the die-off, the phosphorus concentration levels ranged from 0.030 mg/l to 0.140 mg/l. The maximum and mean phosphorus concentration levels increased after zebra mussel arrival and decreased after the die-off (Figures 66 and 67). There was no significant difference (p=0.8040) between treatment means for OOL-2 (Table 10).

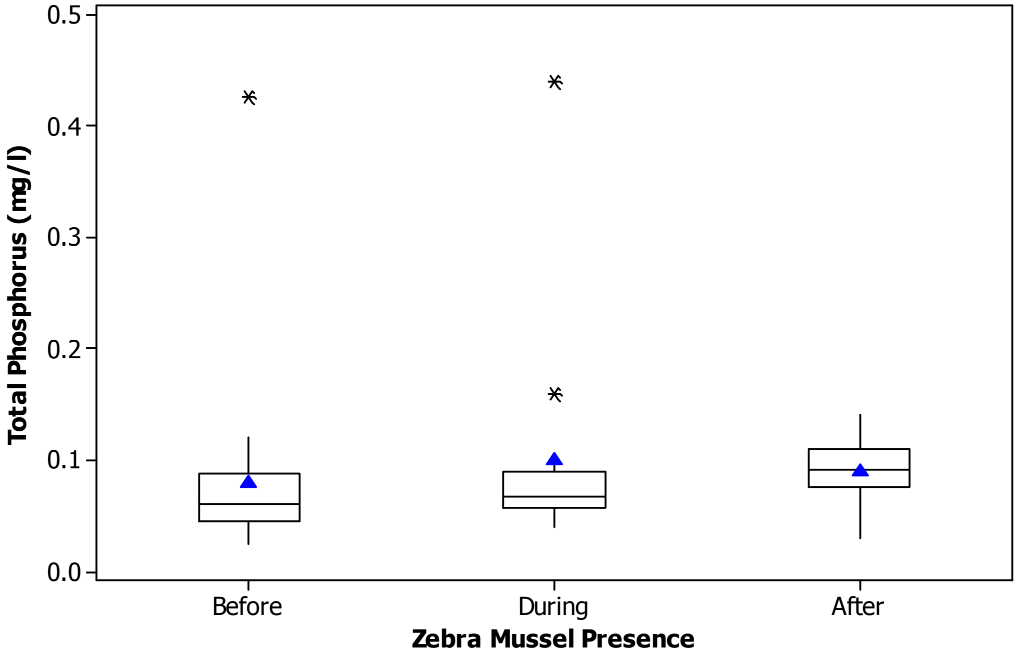

Figure 66. Boxplot of total phosphorus (mg/l) variability across OOL-2 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

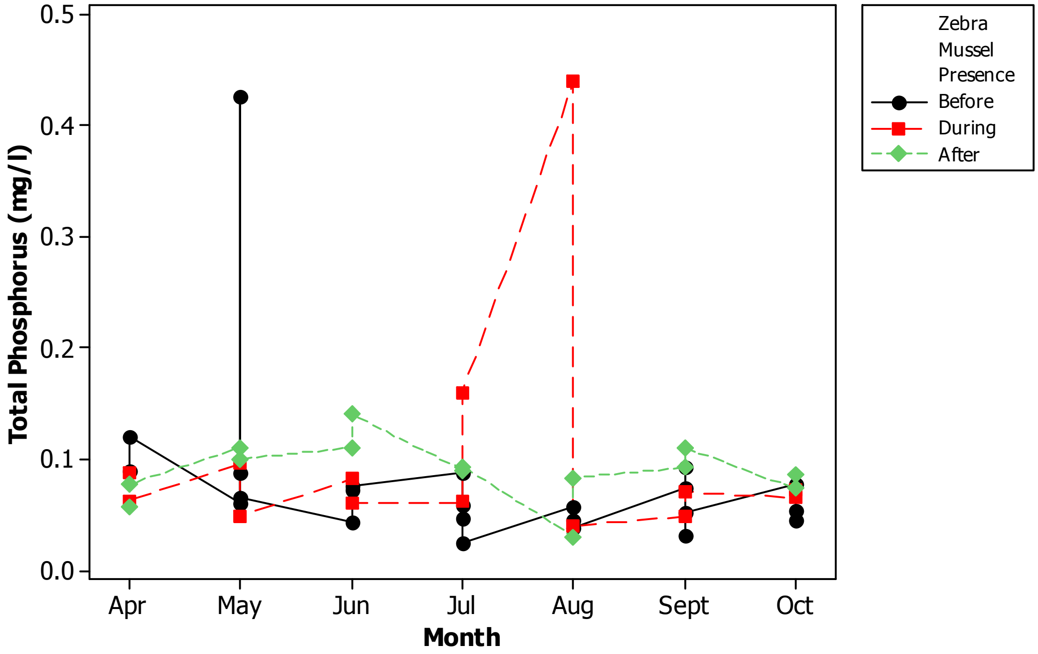

Figure 67. Scatterplot of total phosphorus (mg/l) for OOL-2 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total phosphorus concentration levels for OOL-3 sampling station ranged from 0.040 mg/l to 0.203 mg/l before zebra mussel arrival and ranged from 0.044 mg/l to 0.180 mg/l during zebra mussel presence. After the die-off, the phosphorus concentration levels ranged from 0.027 mg/l to 0.180 mg/l. Unlike phosphorus concentration analysis at OOL-1 and OOL-2, maximum concentration levels at OOL-3 decreased after zebra mussel arrival; however, like the previous stations, the mean phosphorus concentration levels slightly increased (Figures 68 and 69). After the die-off, the *After* treatment mean phosphorus concentration level increased (Figure 68). There was no significant difference (p=0.3173) between treatment means of phosphorus concentration levels at OOL-3 (Table 10).

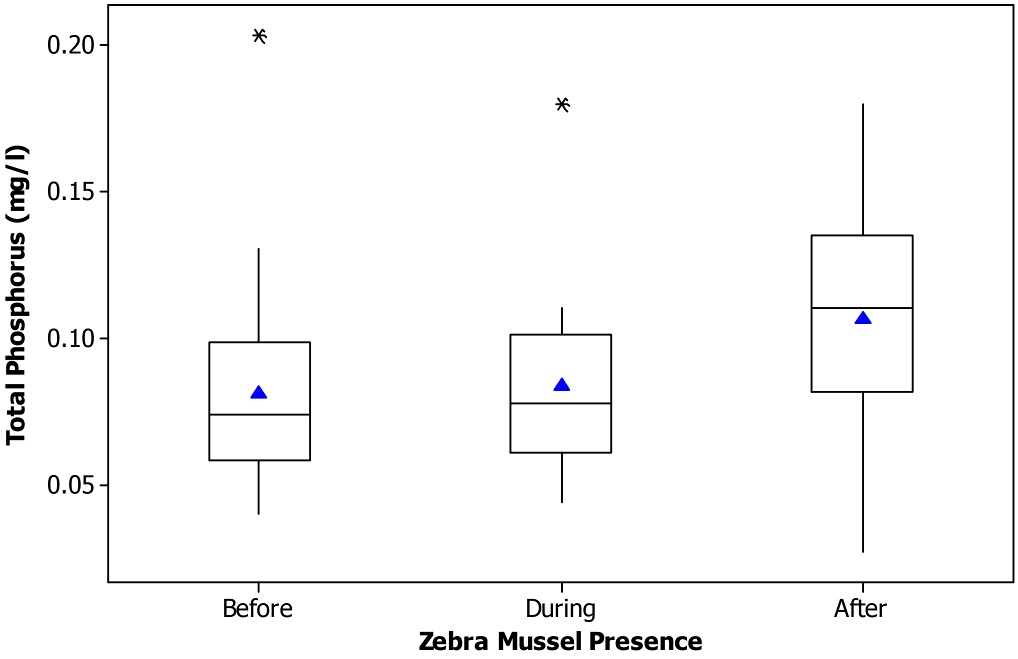

Figure 68. Boxplot of total phosphorus (mg/l) variability across OOL-3 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

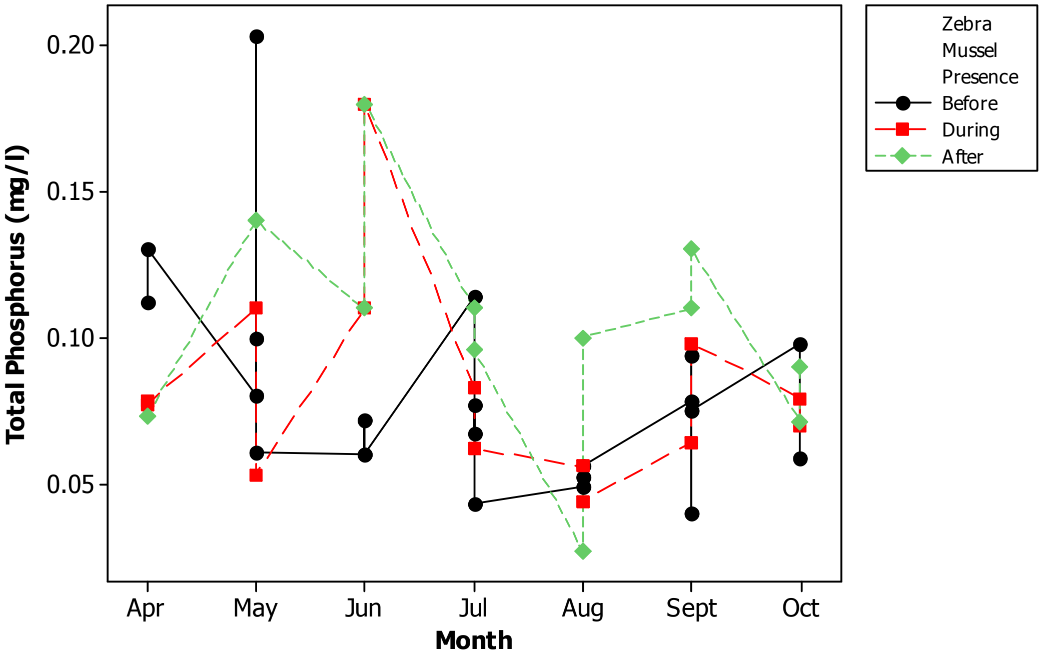

Figure 69. Scatterplot of total phosphorus (mg/l) for OOL-3 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total phosphorus concentration levels for OOL-4 sampling station ranged from 0.055 mg/l to 0.322 mg/l before zebra mussel arrival and ranged from 0.055 mg/l to 0.290 mg/l during zebra mussel presence. After the die-off, the phosphorus concentration levels ranged from 0.037 mg/l to 0.250 mg/l. The maximum phosphorus concentration levels decreased after zebra mussel arrival and continued to decrease after the die-off; however the mean slightly increased after zebra mussel arrival and continued to increase after the die-off while the treatment means increased (Figures 70 and 71). There was no significant difference (p=0.8981) between treatment means of phosphorus concentration levels at OOL-4 (Table 10).

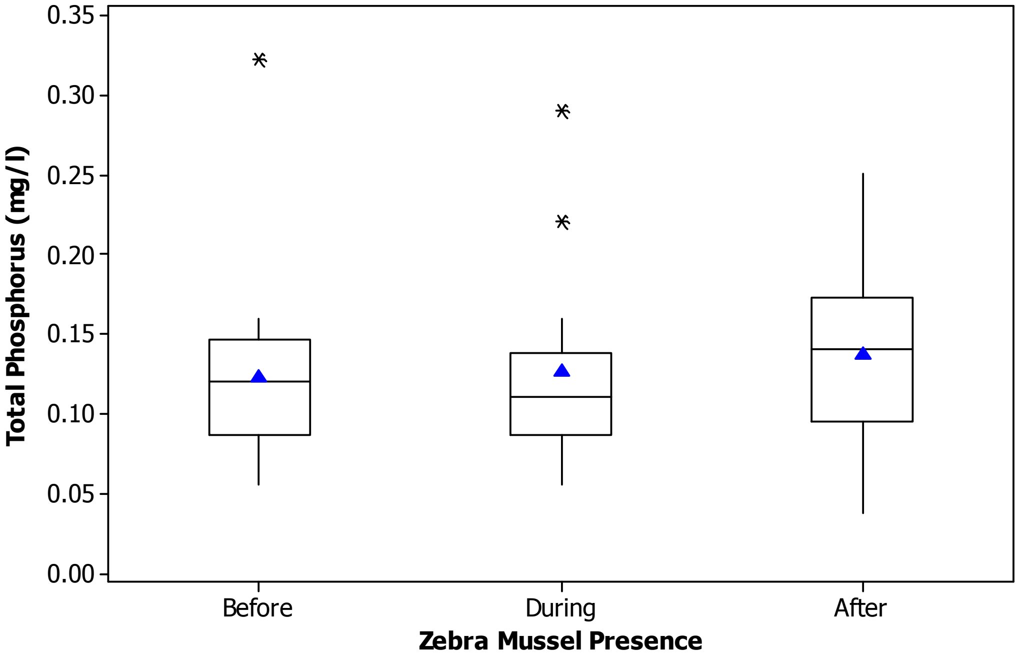

Figure 70. Boxplot of total phosphorus (mg/l) variability across OOL-4 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

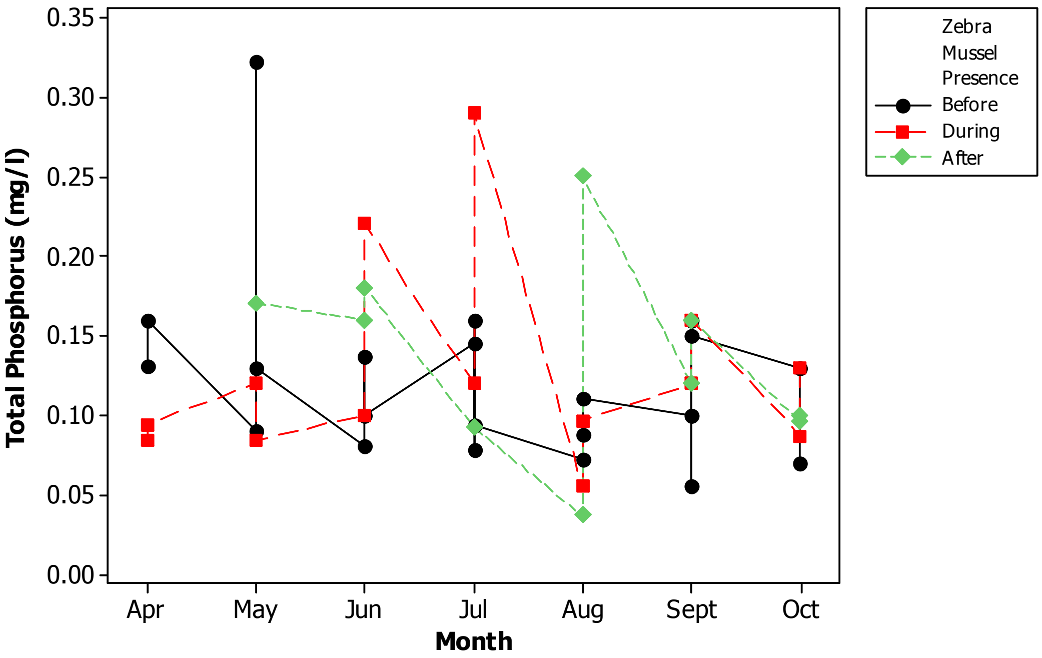

Figure 71. Scatterplot of total phosphorus (mg/l) for OOL-4 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Total phosphorus concentration levels for OOL-5 sampling station ranged from 0.059 mg/l to 0.495 mg/l before zebra mussel arrival and ranged from 0.081 mg/l to 0.340 mg/l during zebra mussel presence. After the die-off, the phosphorus levels ranged from 0.033 mg/l to 0.330 mg/l. The maximum and mean phosphorus concentration levels decreased after zebra mussel arrival and continued to decrease after the die-off (Figures 72 and 73). There was no significant difference (p=0.5091) between treatment means of phosphorus concentration levels at OOL-5 (Table 10).

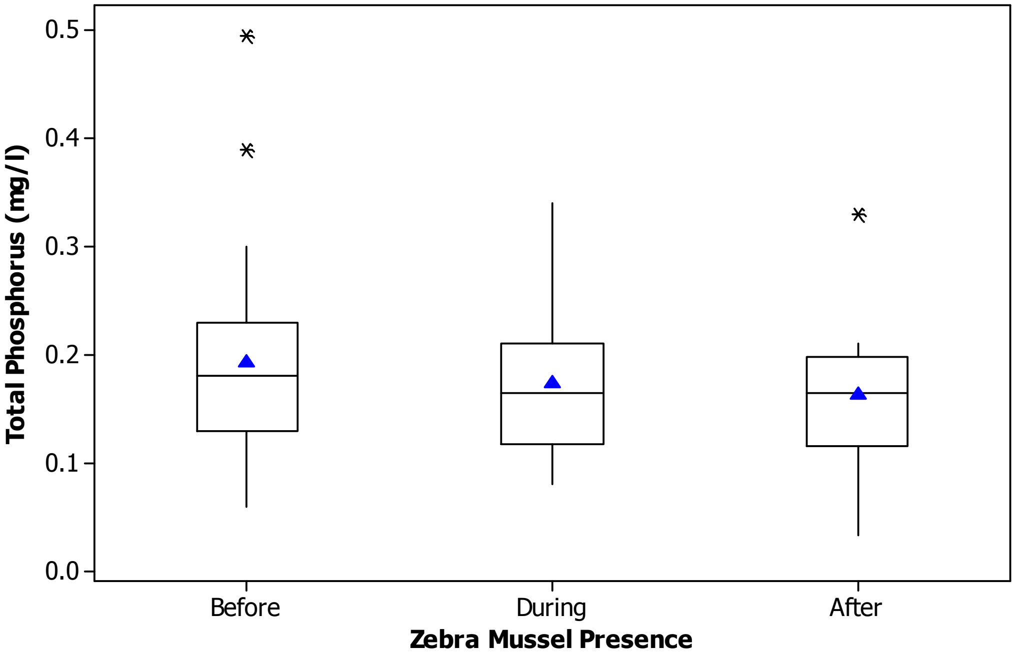

Figure 72. Boxplot of total phosphorus (mg/l) variability across OOL-5 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

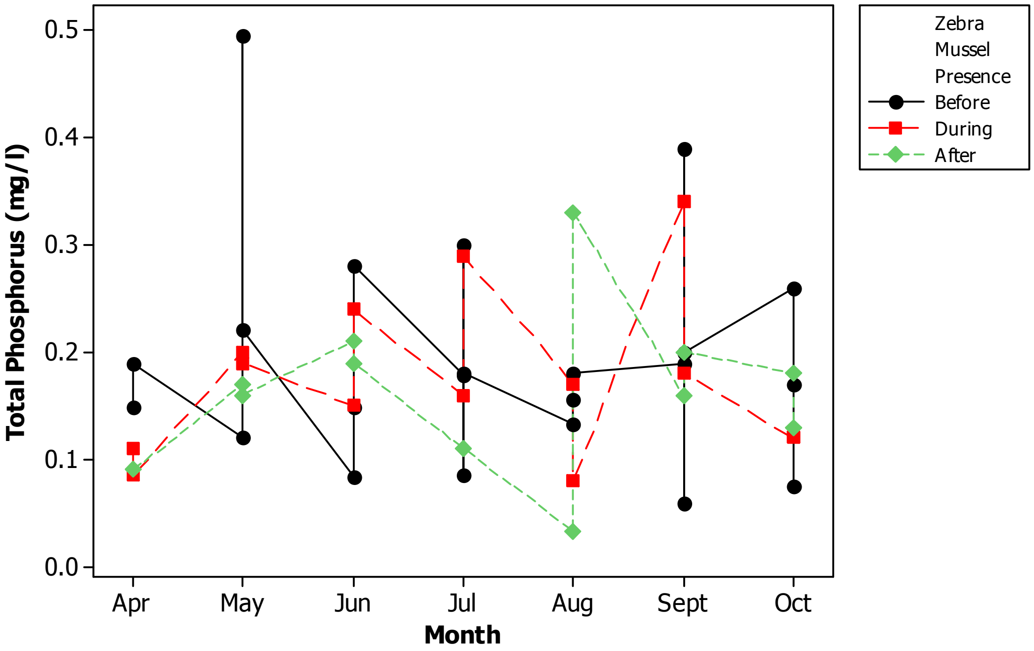

Figure 73. Scatterplot of total phosphorus (mg/l) for OOL-5 sampling station of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

The lowest total phosphorus levels were observed at OOL-1, while the highest concentration levels were observed at OOL-2 and OOL-5. However, if the outliers are not taken into account, the upper limit values at OOL-2 are under 0.20 mg/l across all treatment levels (Figure 66), while the upper limit concentrations at OOL-5 vary from above 0.20 mg/l to about 0.35 mg/l (Figure 72).

Table 8. Descriptive statistics for total phosphorus (mg/l) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	**SE**	**Max**	**Min**	**Number of Obs.**	**Number of Obs. BDL[3]**
Lake-wide						
Before	0.10541	0.007714674	0.495	0.020	111	0
During	0.10831	0.008975041	0.440	0.020	70	0
After	0.11095	0.007048527	0.330	0.030	63	0
OOL-1						
Before	0.05291	0.004146	0.095	0.020	22	0
During	0.05929	0.005787	0.096	0.020	14	0
After	0.07400	0.007766	0.130	0.027	14	0
OOL-2						
Before	0.07913	0.016511	0.427	0.025	23	0
During	0.09943	0.027344	0.440	0.040	14	0
After	0.08921	0.007068	0.140	0.030	14	0
OOL-3						
Before	0.08091	0.007767	0.203	0.040	22	0
During	0.08314	0.009166	0.180	0.044	14	0
After	0.10592	0.010549	0.180	0.027	13	0
OOL-4						
Before	0.12241	0.011726	0.322	0.055	22	0
During	0.12571	0.016525	0.290	0.055	14	0
After	0.13650	0.018893	0.250	0.037	10	0
OOL-5						
Before	0.19286	0.022072	0.495	0.059	22	0
During	0.17400	0.020113	0.340	0.081	14	0
After	0.16358	0.021083	0.330	0.033	12	0

[1] April – October months used in analysis
[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008
[3] BDL=Below Detection Limit

Chlorophyll *a*

Descriptive statistics for phosphorus concentration levels for lake-wide and the five sampling stations are presented in Table 8.

Before zebra mussel presence, lake-wide analysis of chlorophyll *a* results ranged from 1.20 µg/l to 43.10 µg/l; the results ranged from 1.20 µg/l to 60.20 µg/l during zebra mussel presence. After the zebra mussel die-off, chlorophyll *a* concentration levels ranged from below the detection limit (<0.10 µg/l) to 22.80 µg/l. Graphical summaries for the lake-wide results according to zebra mussel presence are presented in Figures 74 and 75. Overall, the lake-wide chlorophyll *a* maximum and mean concentration levels increased after zebra mussel arrival and decreased after the die-off. There was no significant difference (p=0.1798) between treatment means for the lake-wide analysis of chlorophyll *a* concentration levels (Table 10).

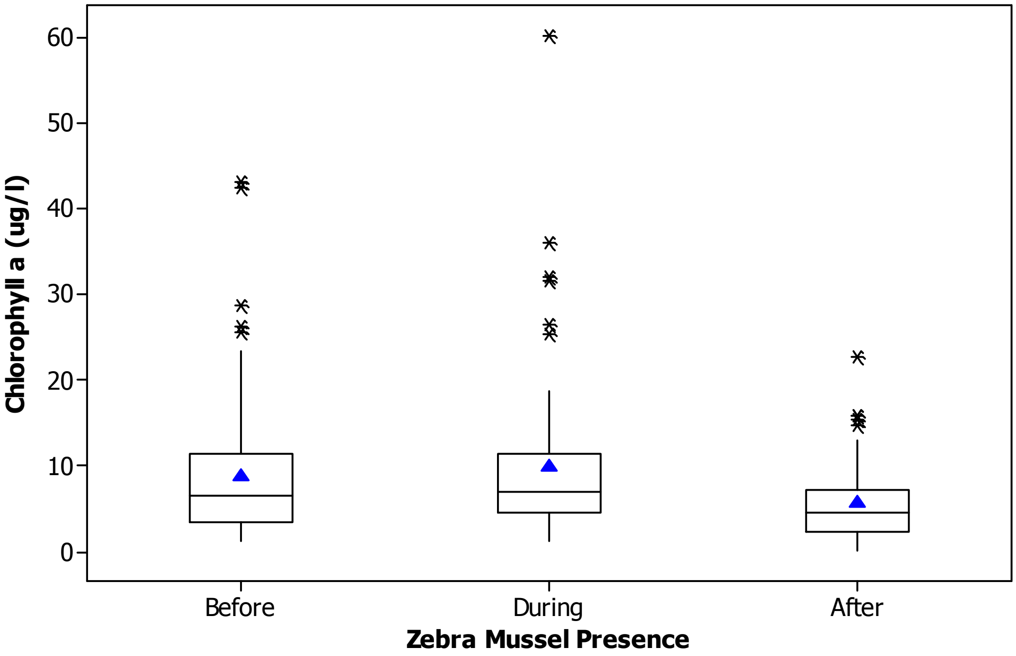

Figure 74. Boxplot of chlorophyll *a* (µg/l) variability across all stations of Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

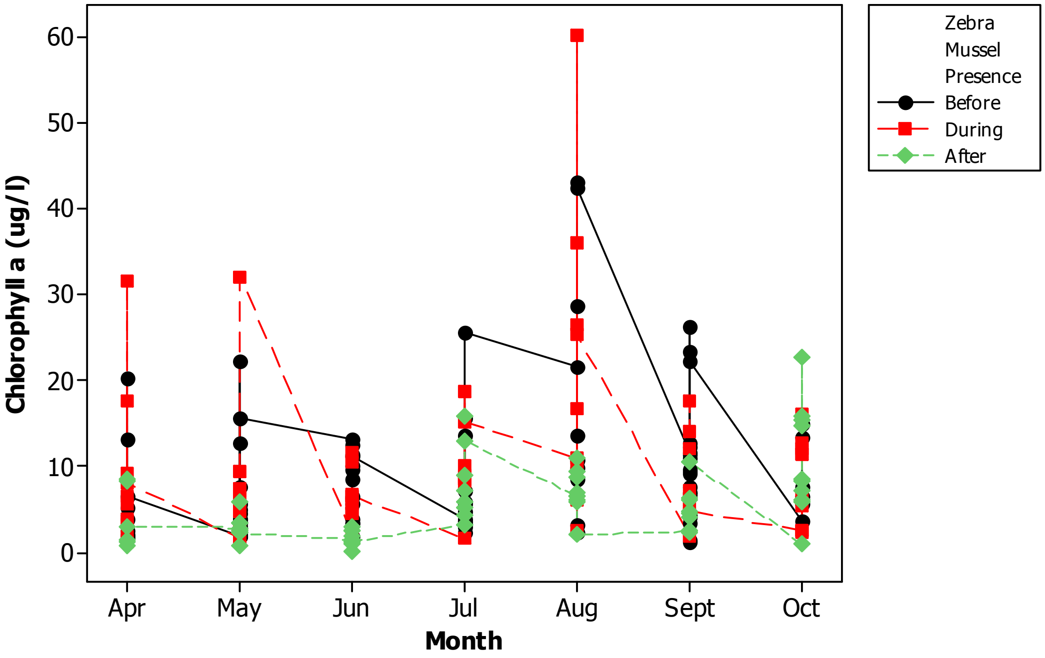

Figure 75. Scatterplot of chlorophyll *a* (µg/l) for all stations of Oologah Lake for April – October of the 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Chlorophyll *a* concentration levels for OOL-1 sampling station ranged from 1.20 µg/l to 21.50 µg/l before zebra mussel arrival and ranged from 1.20 µg/l to 10.90 µg/l during zebra mussel presence. After the die-off, the chlorophyll *a* levels ranged from 0.90 µg/l to 8.40 µg/l. The maximum chlorophyll *a* concentration levels at OOL-1 decreased after zebra mussel arrival and continued to decrease after the die-off; however, the mean concentration level increased after the die-off (Figures 76 and 77). There was no significant difference (p=0.4951) between chlorophyll *a* treatment means at OOL-1 (Table 10).

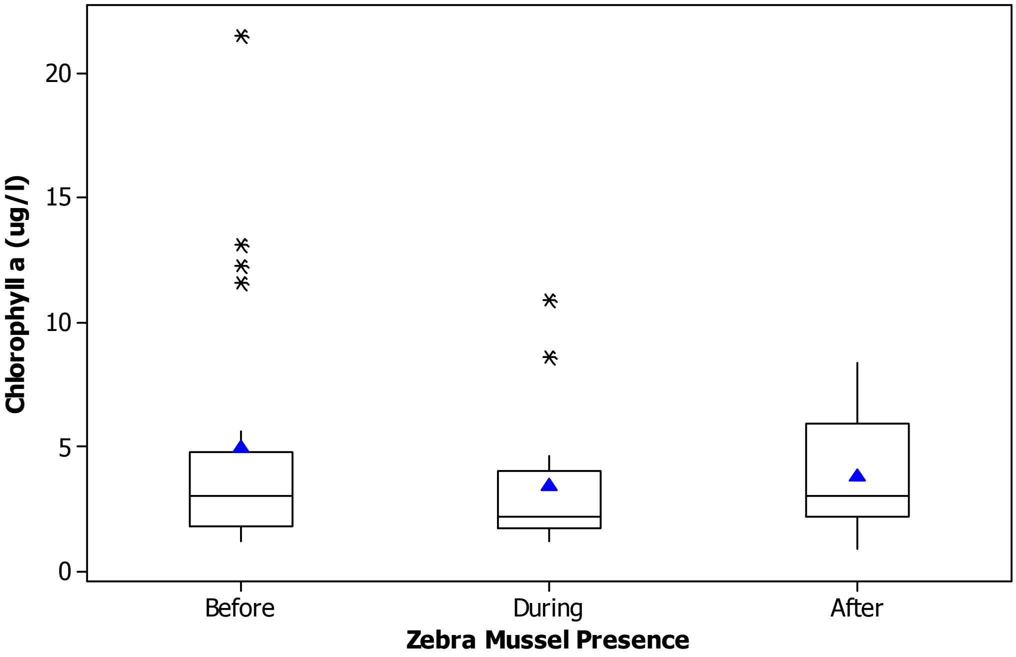

Figure 76. Boxplot of chlorophyll *a* (µg/l) variability across OOL-1 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

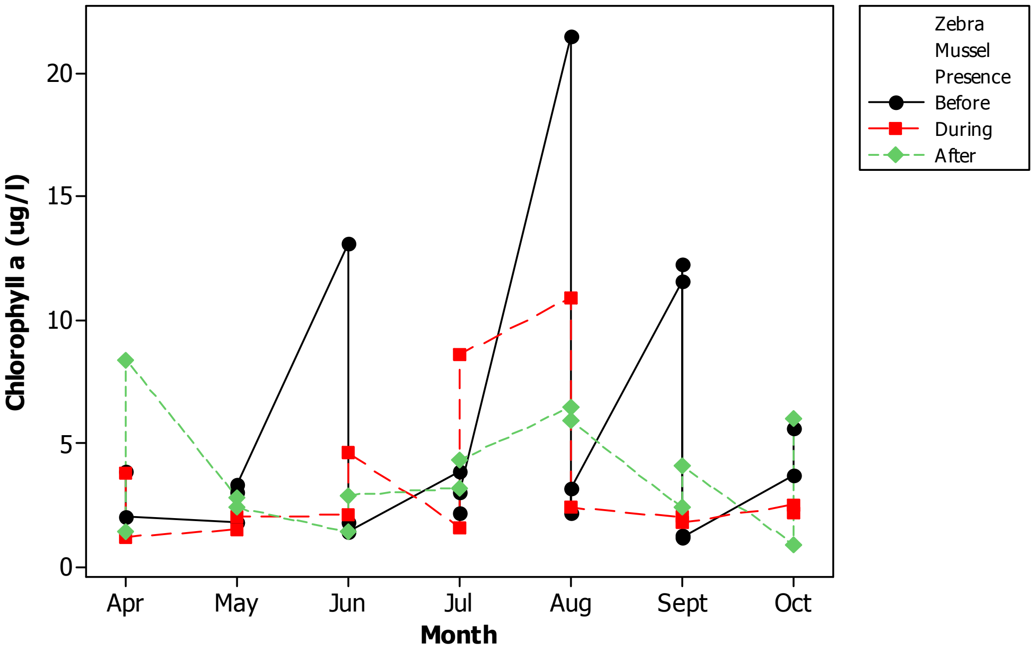

Figure 77. Scatterplot of chlorophyll *a* (µg/l) for OOL-1 sampling station of Oologah Lake for April – October of the 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Chlorophyll *a* concentration levels for OOL-2 sampling station ranged from 1.30 µg/l to 13.70 µg/l before zebra mussel arrival and ranged from 1.40 µg/l to 26.40 µg/l during zebra mussel presence. After the die-off, the chlorophyll *a* levels ranged from 0.80 µg/l to 9.00 µg/l. The maximum and mean chlorophyll *a* concentration levels at OOL-2 increased after zebra mussel arrival and decreases after the die-off (Figures 78 and 79). There was no significant difference (p=0.2147) between chlorophyll *a* treatment means at OOL-2 (Table 10).

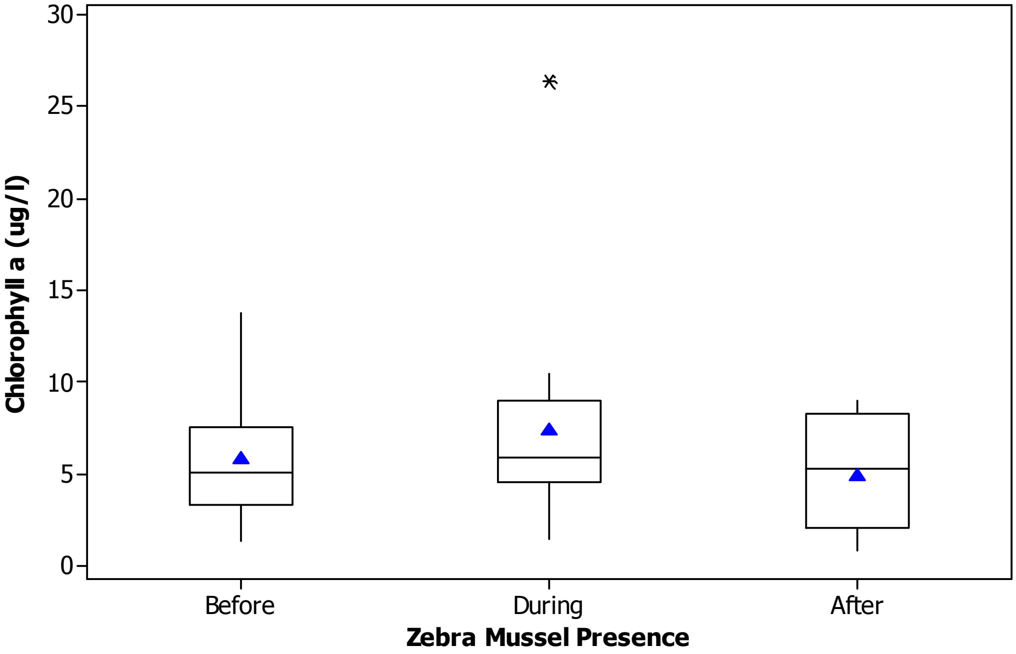

Figure 78. Boxplot of chlorophyll *a* (µg/l) variability across OOL-2 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

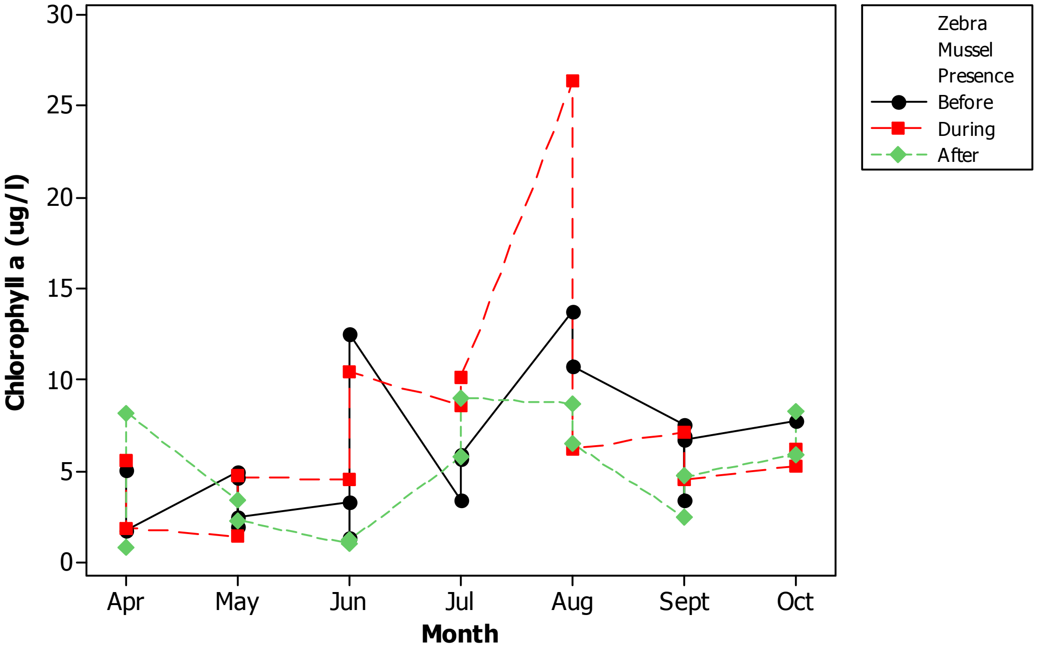

Figure 79. Scatterplot of chlorophyll *a* (µg/l) for OOL-2 sampling station of Oologah Lake for April – October of the 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Chlorophyll *a* concentration levels for OOL-3 sampling station ranged from 1.90 µg/l to 10.80 µg/l before zebra mussel arrival and ranged from 2.50 µg/l to 36.00 µg/l during zebra mussel presence. After the die-off, the chlorophyll *a* levels ranged from 1.10 µg/l to 8.50 µg/l. The maximum and mean chlorophyll *a* concentration levels at OOL-3 increased after zebra mussel arrival and decreased after the die-off (Figures 80 and 81). There was no significant difference (p=0.3240) between chlorophyll *a* treatment means at OOL-3 (Table 10).

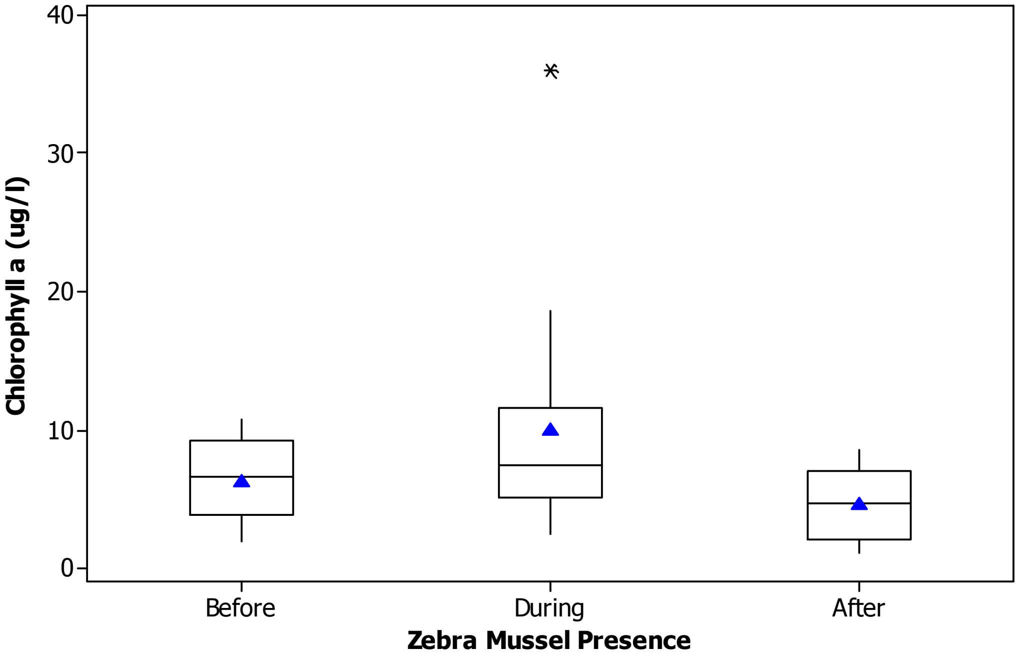

Figure 80. Boxplot of chlorophyll *a* (µg/l) variability across OOL-3 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

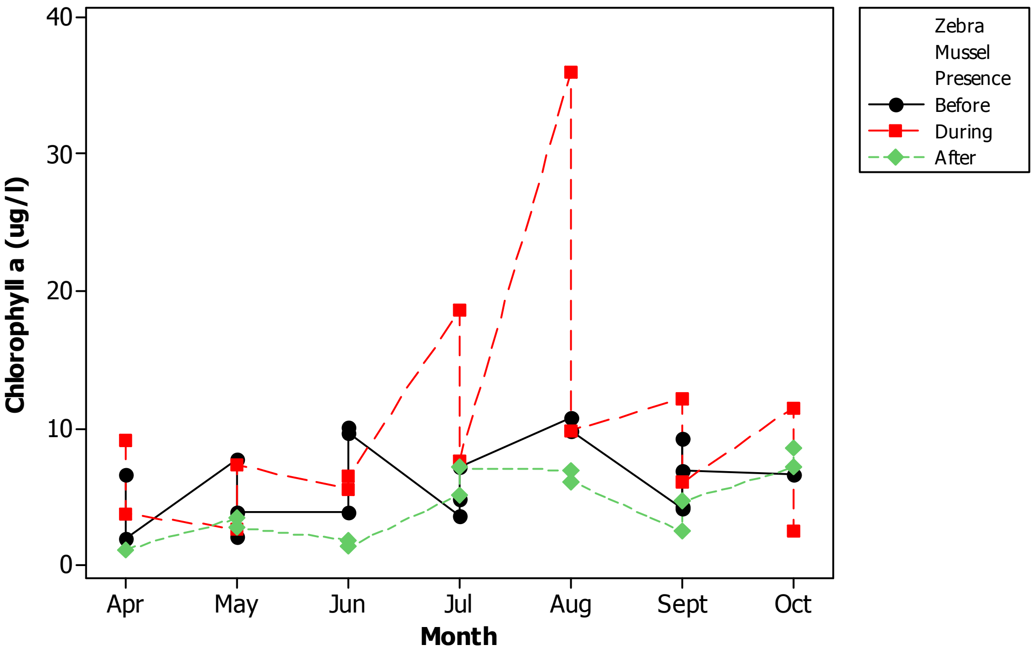

Figure 81. Scatterplot of chlorophyll *a* (µg/l) for OOL-3 sampling station of Oologah Lake for April – October of the 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Chlorophyll *a* concentration levels for OOL-4 sampling station ranged from 1.90 µg/l to 28.80 µg/l before zebra mussel arrival and ranged from 5.10 µg/l to 17.50 µg/l during zebra mussel presence. After the die-off, the chlorophyll *a* levels ranged from 0.80 µg/l to 15.90 µg/l. The maximum and mean chlorophyll *a* concentration levels at OOL-4 decreased after zebra mussel arrival and continued to decrease after the die-off (Figures 82 and 83). There was no significant difference (p=0.5358) between chlorophyll *a* treatment means at OOL-4 (Table 10).

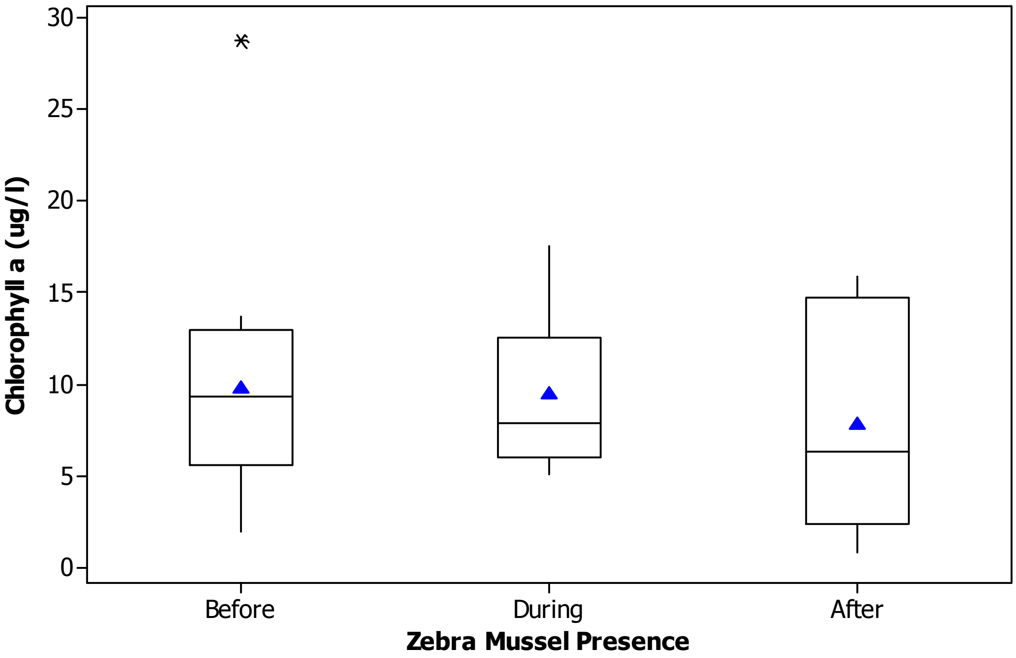

Figure 82. Boxplot of chlorophyll *a* (µg/l) variability across OOL-4 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

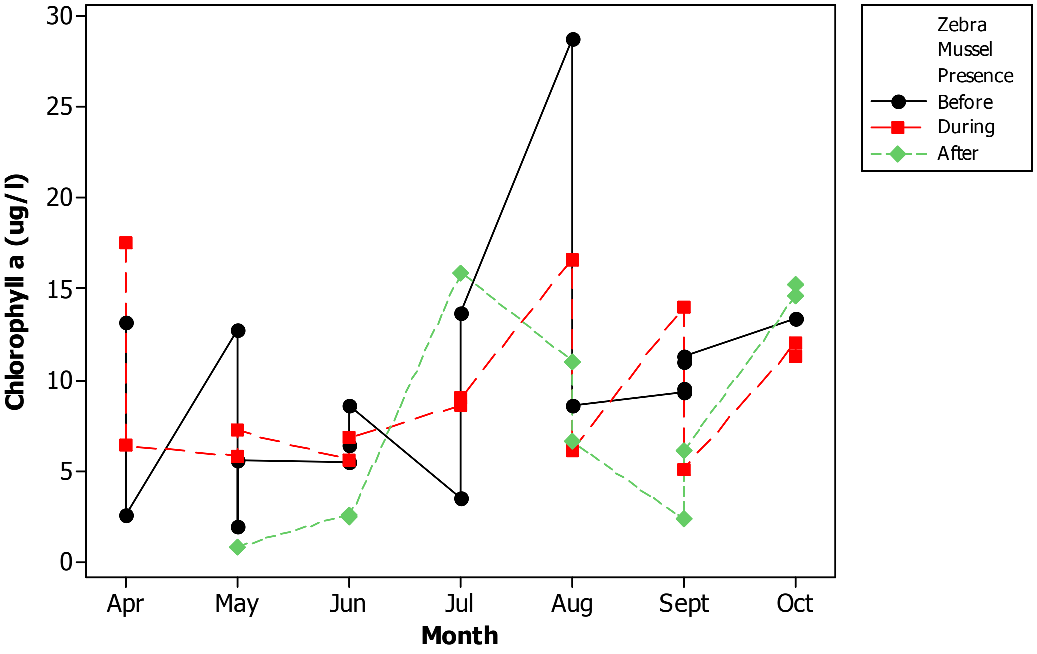

Figure 83. Scatterplot of chlorophyll *a* (µg/l) for OOL-4 sampling station of Oologah Lake for April – October of the 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

Chlorophyll *a* concentration levels for OOL-5 sampling station ranged from 2.70 µg/l to 43.10 µg/l before zebra mussel arrival and ranged from 4.80 µg/l to 60.20 µg/l during zebra mussel presence. After the die-off, the chlorophyll *a* levels ranged from below the detection limit (<0.10 µg/l) to 22.80 µg/l. The maximum and mean chlorophyll *a* concentration levels at OOL-5 decreased after zebra mussel arrival and decreased after the die-off (Figures 84 and 85). There was significant difference between treatment chlorophyll *a* treatment means (p=0.0088) at OOL-5 (Table 10). Post hoc comparison showed the *After* treatment mean was significantly different from the *Before* and *During* treatment means (p=0.0048 and p=0.0084, respectively); however the *Before* and *During* treatment means were not significantly different (p=0.8776) (Table 10).

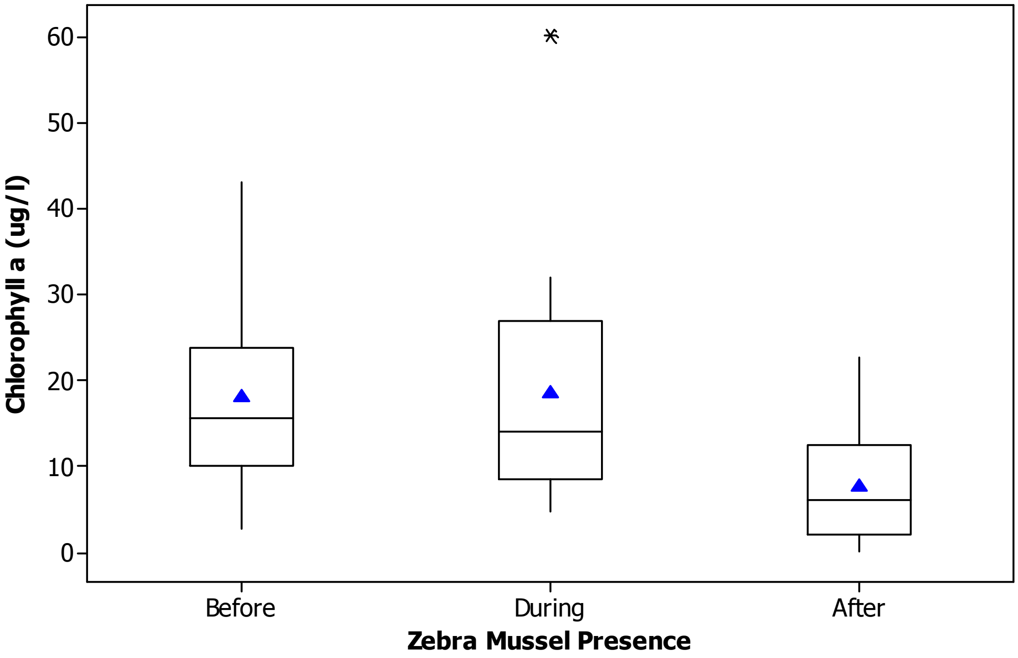

Figure 84. Boxplot of chlorophyll *a* (µg/l) variability across OOL-5 sampling station Oologah Lake for April – October of 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

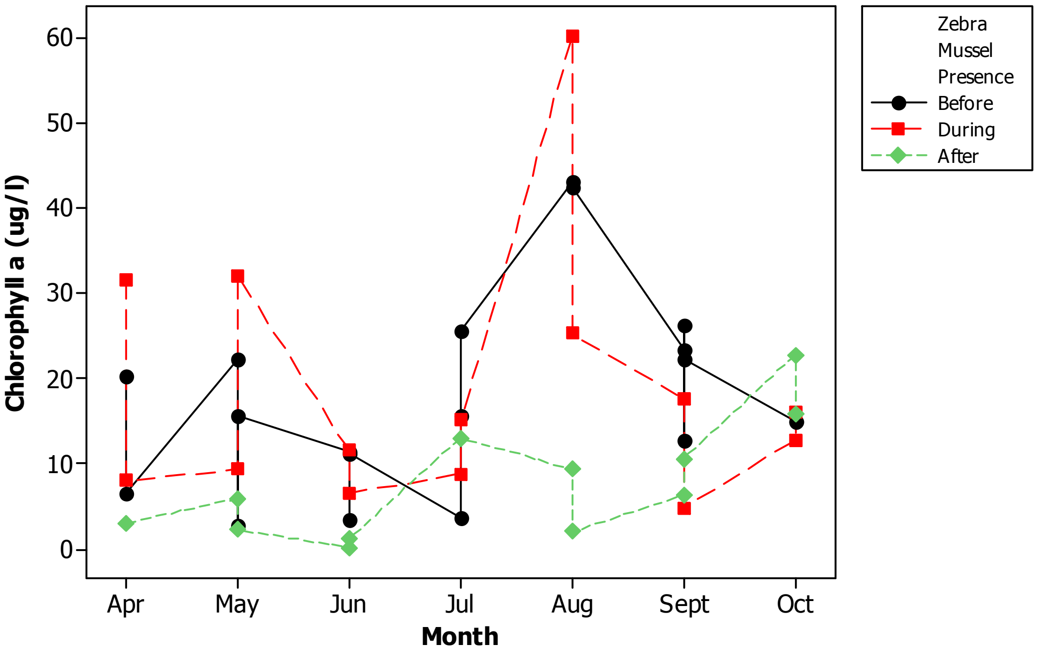

Figure 85. Scatterplot of chlorophyll *a* (µg/l) for OOL-5 sampling station of Oologah Lake for April – October of the 2000 – 2008 study period; *Before* (2000 – 2002), *During* (2004 – 2005), *After* (2007 – 2008).

While no significant differences were noted at OOL-1, notable decreases in chlorophyll *a* concentrations occurred during June, August, and September after the zebra mussel arrival (Figure 77). There was not a notable decrease, but rather a noted increase in chlorophyll *a* concentration at OOL-2 during August in the *During* treatment period (Figures 79), as well as at OOL-3 in July and August (Figure 81). At OOL-4, the most notable decrease in chlorophyll *a* occurred in September during the *During* and *After* study periods.

Table 9. Descriptive statistics for chlorophyll *a* (µg/l) at Oologah Lake for the 2000 – 2008[1] sampling period by treatment level[2].

	Mean	**SE**	**Max**	**Min**	**Number of Obs.**	**Number of Obs. BDL[3]**
Lake-wide						
Before	8.71383	0.83003	43.10	1.20	94	0
During	9.72143	1.14996	60.20	1.20	70	0
After	5.53651	0.57010	22.80	<0.10	62	1
OOL-1						
Before	4.9429	1.14406	21.50	1.20	21	0
During	3.3714	0.77029	10.90	1.20	14	0
After	3.7571	0.59316	8.40	0.90	14	0
OOL-2						
Before	5.7684	0.80670	13.70	1.30	19	0
During	7.3500	1.62345	26.40	1.40	14	0
After	4.8786	0.80719	9.00	0.80	14	0
OOL-3						
Before	6.1526	0.64220	10.80	1.90	19	0
During	9.9000	2.30861	36.00	2.50	14	0
After	4.4692	0.69866	8.50	1.10	13	0
OOL-4						
Before	9.7471	1.50761	28.80	1.90	17	0
During	9.4286	1.11717	17.50	5.10	14	0
After	7.7600	1.88002	15.90	0.80	10	0
OOL-5						
Before	17.9500	2.77095	43.10	2.70	18	0
During	18.5571	3.96729	60.20	4.80	14	0
After	7.6833	1.98997	22.80	<0.10	11	1

[1] April – October months used in analysis

[2] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 - 2008

[3] BDL=Below Detection Limit

Table 10. P values from Analysis of Covariance[1] for all listed parameters at Oologah Lake for the 2000 – 2008[2, 3]study period.

Station Post Hoc[4]	**Secchi depth**	**Turbidity**	**Total Suspended Solids**	**Dissolved Oxygen**	**Total Ammonia**	**Total Phosphorus**	**Chlorophyll *a***
Lake-wide	p=0.3305	p=0.1004	p=0.1179	p=0.0856	**p=0.0166**	p=0.8294	p=0.1798
B/D	N/A	N/A	N/A	N/A	**p=0.0284**	N/A	N/A
B/A	N/A	N/A	N/A	N/A	p=0.1266	N/A	N/A
D/A	N/A	N/A	N/A	N/A	**p=0.0048**	N/A	N/A
OOL-1	p=0.4092	p=0.2994	p=0.3729	p=0.3067	**p=0.0493**	**p=0.0436**	p=0.4951
B/D	N/A	N/A	N/A	N/A	**p=0.0324**	p=0.4627	N/A
B/A	N/A	N/A	N/A	N/A	p=0.7937	**p=0.0134**	N/A
D/A	N/A	N/A	N/A	N/A	**p=0.0290**	p=0.1014	N/A
OOL-2	p=0.2537	p=0.2051	p=0.4461	p=0.0728	**p=<0.0001**	p=0.8040	p=0.2147
B/D	N/A	N/A	N/A	N/A	**p=0.0006**	N/A	N/A
B/A	N/A	N/A	N/A	N/A	**p=<0.0001**	N/A	N/A
D/A	N/A	N/A	N/A	N/A	**p=<0.0001**	N/A	N/A
OOL-3	p=0.2399	p=0.2416	p=0.4118	**p=0.0409**	**p=<0.0001**	p=0.3173	p=0.3240
B/D	N/A	N/A	N/A	p=0.2482	**p=0.0015**	N/A	N/A
B/A	N/A	N/A	N/A	p=0.1085	**p=<0.0001**	N/A	N/A
D/A	N/A	N/A	N/A	**p=0.0124**	**p=<0.0001**	N/A	N/A
OOL-4	p=0.4893	p=0.1844	p=0.9329	p=0.1292	p=0.1092	p=0.8981	p=0.5358
B/D	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OOL-5	p=0.4378	p=0.1222	p=0.2560	p=0.3220	p=0.0865	p=0.5091	**p=0.0088**
B/D	N/A	N/A	N/A	N/A	N/A	N/A	p=0.8776
B/A	N/A	N/A	N/A	N/A	N/A	N/A	**p=0.0048**
D/A	N/A	N/A	N/A	N/A	N/A	N/A	**p=0.0084**

[1] Significance determined at α=0.05

[2] April – October months used in analysis

[3] *Before*: 2000 – 2002; *During*: 2004 – 2005; *After*: 2007 – 2008

[4] Post hoc comparison between treatment means if applicable; B=*Before*, D=*During*, A=*After*

CHAPTER V

DISCUSSION

Overall, lake-wide results from this study indicate that zebra mussels had no significant impact on water clarity measurements or on dissolved oxygen, total phosphorus, or chlorophyll *a* concentration levels in Oologah Lake. Total ammonia concentration was the only water quality parameter in this study that resulted in a lake-wide significant decline in mean concentration levels after zebra mussel arrival (Table 10). This is noted with the caveat of different detection limits used throughout the 2000 – 2008 study period (Table 2) and the method of using the detection limit as the value in the statistical analysis. The trend in total ammonia means across treatment periods in this study is not typical: the significant decrease in ammonia concentration after the arrival and then the significant increase after the die-off. Previous studies (Holland *et al.*, 1995; Effler *et al.*, 1996; Effler *et al.*, 2004) report increases in total ammonia concentration levels due to direct and indirect zebra mussel metabolic activities. Zebra mussels can impact ammonia concentration levels directly by excretion and indirectly by grazing on phytoplankton in enough quantities, leaving the nutrient available in the system (Effler *et al.*, 1996). The significant increase of ammonia concentration levels after the die-off, however, may have been attributed to the die-off itself; zebra mussels are also noted as releasing ammonia back into the system through death (Holland *et al.*, 1995).

Although no lake-wide significance occurred for other water quality parameters measured in this study, there were some significant differences seen at individual sampling stations for total phosphorus, dissolved oxygen, and chlorophyll *a* concentration levels at individual sites (OOL-1, OOL-3, and OOL-5, respectively). Analysis of the mean total phosphorus concentration levels at OOL-1 (the deepest station of the lake) resulted in a significant increase after the zebra mussel die-off from before the zebra mussel invasion; however, there was no significant difference in mean concentration levels between the *During* treatment period and the other two treatment periods (*Before* and *After*). Assuming that zebra mussels would have impacted the water quality parameter concentration levels in a system, lack of other significant differences in total phosphorus concentration levels occurring in Oologah Lake is in line with other studies; Holland *et al.* (1995) reported this trend in Lake Erie. James *et al.* (2001) reported that while the efficiency of zebra mussels filtering capabilities can clarify a water column, release of nutrients (which contains phosphorus) back into the system via excretion does occur. If this happens in high enough concentrations it can, in turn, impact phytoplankton dynamics (James *et al.*, 2001), which then continues the domino effect and can impact chlorophyll *a* concentration levels and water clarity measurements.

The only significant change in dissolved oxygen levels over the treatment periods occurred at OOL-3 (mid-lake station). A significant decrease in dissolved oxygen concentration levels occurred after the zebra mussel die-off, which is uncharacteristic compared to previous reports: the higher the population density of zebra mussels, the higher the rate of oxygen consumption. Oddly enough, it was during the zebra mussel presence that this station exhibited higher dissolved oxygen concentration means. Caraco *et al.* (2000) report from their study that even a moderately-sized population of zebra mussels could impact dissolved oxygen concentrations; however, it was also noted that the interaction of other physical and biological parameters in the system play a key role in determining to what degree zebra mussels will impact the dissolved oxygen concentrations within the system. This may be the case with the Oologah Lake system.

Lake-wide analysis of chlorophyll *a* concentrations did not result in a significant difference between before zebra mussel arrival, during their arrival, or after their die-off; however, individual station analysis revealed that the mean chlorophyll *a* concentration levels significantly decreased at OOL-5 (most upstream station of the lake) after the zebra mussel die-off. While a significant decrease was noted in the mean chlorophyll *a* concentration after the zebra mussel die-off at OOL-5, there was no significant difference in water clarity at this site, or lake-wide. This, again, is not typical of a system invaded by zebra mussels, as previously studied (Effler *et al.*, 1996; Effler *et al.*, 2004; Mellina *et al.*, 1995). As noted previously from James *et al.* (2001), release of phosphorus back into the system can alter phytoplankton densities. Chlorophyll *a* concentration measurements estimate the algal biomass of a system; Higgins *et al.* (2010), in their meta-analysis of various systems studied, reported that while some algal group's biomass decline, some are unchanged after zebra mussel invasion.

Statistical analysis of all three water clarity parameters measured for the lake (Secchi depth, turbidity, and total suspended solids) did not show a significant difference between treatment means for the study period. MacIsaac's (1996) study on the impacts that zebra mussels have had on water clarity in the waters of North America noted that changes mainly occurred in shallow and well-mixed lakes and embayments. This may be the case with Oologah Lake, the maximum lake depth during zebra mussel presence was 23.5 m and after the zebra mussel population die-off the maximum lake depth was 28.2 m, both measurements were recorded at the dam site station OOL-1 (mean depths of 11.2 m and 13.4 m, respectively); Mellina *et al.* (1995) reported Lake Erie's mean depth as 7.6 m in the western basin and Holland (1993) reported the maximum depth of 5.3 m in the Hatchery Bay area in the western part of the lake, where significant water clarity changes occurred after zebra mussel invasion.

As with any invasive species that is introduced and becomes established in a new ecosystem, the degree of impact that the species have on the new environment is directly related to the invading species' population size (Strayer and Malcom, 2006; Naddafi *et al.*, 2010). Research on the Seneca River reported the most evident zebra mussel impacts on water quality parameters on a riverine ecosystem, which was attributed to, in part, by higher zebra mussel densities and shallow depth (Effler *et al.*, 2004); one 1.4 km section of the Seneca River had a zebra mussel population density of approximately 50,000 individuals/m^2 (Effler *et al.*, 1998). Western Lake Erie water quality parameter changes can be attributed to the high population density and subsequent high per capita clearance rate of the zebra mussel in western Lake Erie (MacIsaac *et al.*, 1992). In 1992, MacIsaac *et al.* reported one of the highest zebra mussel population densities to date in western Lake Erie, estimated between 253,000 individuals/m^2 and 268,000 individuals/m^2; however Arnott and Vanni (1996) noted densities reaching to 700,000 individuals/m^2 in the western basin of the lake, which was just below the highest zebra mussel population density of 800,000 individuals/m^2 recorded for North America (Ram *et al.*, 1996). Boeckman and Bidwell (2008) reported a zebra mussel population die-off in June 2006 at

Oologah Lake, in doing so, they noted that the adult zebra mussel population went from approximately 150,000 individuals/m^2 to less than 4,500 individuals/m^2. While further analysis in zebra mussel density comparisons would be useful and benefit from further research, the number of zebra mussel density per volume of water may be misleading, as zebra mussels are not evenly distributed throughout a lake or river system, as preferred substrate (i.e. rocky substrate) differs in abundance and spatial location throughout the lake or along rivers. Therefore, location of water samples in proximity to zebra mussel population may play a role in analyzing water quality impacts post- zebra mussel invasion, especially in a lake system. This was noted in the MacIsaac *et al.* (1992) study, where filtering impacts (by both veliger and adult zebra mussels) that are reported from zebra mussel sampling sites would not necessarily apply to the entire lake.

In Oologah Lake, sampling stations for water quality parameter analysis were not picked to coincide with zebra mussel population locations; they were picked due to being historical and consistent sampling sites. Zebra mussels were sampled at Spencer Creek, Blue Creek, Redbud Marina, and Hawthorne Bluff at Oologah Lake to correspond with previous zebra mussel sampling efforts and population density counts (Boeckman and Bidwell, 2010). The only water quality sampling station in this study that is in close proximity of a zebra mussel sampling site is OOL-1. OOL-1 station is over the river channel by the dam, east of Hawthorne Bluff and west of Redbud Marina. The other zebra mussel sampling sites (Spencer Creek and Blue Creek) are isolated in the two coves upstream of the dam site, on the east side of the lake. All water quality sampling stations are in the pelagic waters of the lake over the deepest part of the main river channel (Figure 1). Additionally, three sites (OOL-3, OOL-4, and OOL-5) are upstream from all four of the zebra mussel sampling sites. As an example of how water sampling stations in relation to zebra mussel population location can affect water quality parameter analysis, Secchi disk depth measurements at Redbud Marina ranged from 0.6 m to 1.6 m from January through September 2010 when adult zebra mussel density peaked 60 individuals/m^2 (Boeckman and Bidwell, 2010) compared to Secchi depth measurements of 0.3 m to 1.6 m at OOL-1 sampling station during a population estimate of approximately 150,000 individuals/m^2. This suggests that there is an increase in water clarity, as indicated by Secchi depth measurements, in direct relation to zebra mussel population locations within the lake. Further research and analysis of water quality parameter concentrations at varying distances from zebra mussel population locations would give insight to the extent of zebra mussel filtering activities on a lake system, especially Oologah Lake.

One factor in this study, not taken into consideration in previous research, is the hydraulic residence time. Hydraulic residence time is a key parameter in a lake system which impacts the water quality analyses of any aquatic system. What may be unique to this study is that the outflow from Oologah Lake is controlled (by the U.S. Army Corps of Engineers) for navigation, flood control, recreation, and fish and wildlife purposes. Navigation purposes for the McClellan-Kerr Arkansas River Navigation System requires a coordinated effort to schedule releases from area Corps' projects to provide enough water downstream in order to maintain required depths along the navigation channel. When major rain events occur, flood control would take higher precedence. For this study, it was determined that the controlled releases from the Oologah Dam was the limiting factor affecting the amount of time that the river water spends in the lake system;

therefore the release volumes from the dam were used in the calculations of hydraulic residence times (Williams pers. comm., 2010). The use of hydraulic residence time as a covariate was necessary to isolate any water quality impacts zebra mussels have on Oologah Lake's natural system. Quinn (1992) recorded the hydraulic residence times for each of the Great Lakes; Lake Erie had a hydraulic residence time of 2.7 years, Lake Huron was 21 years, with the highest hydraulic residence time of 173 years was reported for Lake Superior. In comparison, Oologah Lake's calculated hydraulic residence times for each sampling date was below 1 year 75% of the time and below 6 months 65% of the time. The lower reported hydraulic residence times at Oologah Lake are important to note; the less time that the water stayed in the system, the less time it was available to be utilized and impacted by the biological and water chemistry needs of the system.

CHAPTER VI

CONCLUSION

Oologah Lake is a large tributary to the Arkansas River in Oklahoma, which provides flows for flood control and navigation purposed for the McClellan-Kerr Arkansas River Navigation System in Oklahoma. The results from this study indicate that zebra mussels have had little impact on water clarity measurements, dissolved oxygen, total phosphorus, and chlorophyll *a* concentrations at Oologah Lake. The impact on total ammonia was significant; however, the inconsistency with detection limit values used may have skewed the data for analysis.

Zebra mussel densities and location of water samples taken within Oologah Lake may have attributed to the lack of significant changes in the water quality parameters measured during the study period. For this study, historical water quality sampling stations provided data pre- and post- zebra mussel invasion in the system. The water samples were taken at 0.5 m below the surface over the river channel, not near known zebra mussel population locations. Further research on water quality measurements with regard to proximity to zebra mussel population location would assist in understanding the extent to which zebra mussels may impact water quality parameter values at Oologah Lake.

Furthermore, this study used hydraulic residence time as the covariate in statistical analysis of covariance, as hydraulic residence time plays a key role in a lake system and determines the time that the water is available for biochemical processes within the system; most previous studies used either ANOVA or MANOVA in their analyses. This study incorporates and uses hydraulic residence time as a covariate in order to isolate the impacts from zebra mussels by recognizing and accounting for the impacts that hydrology has on water quality parameter measurements at Oologah Lake. In lake systems with longer hydraulic residence times, it would be expected that zebra mussel filtering activity would have a greater impact on water clarity and other water quality parameters of the system, as seen in the Lake Erie studies where the lake is noted as being a static and shallow lake, with a longer residence time.

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APPENDICES

Appendix 1. Sampling dates and parameters sampled by station at Oologah Lake for the 2000 – 2008 study period.

Station	**Secchi**	**Turbidity**	**Total Suspended Solids**	**Dissolved Oxygen**	**Total Ammonia**	**Total Phosphorus**	**Chlorophyll *a***
OOL-1	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00
	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00
	-	-	-	-	-	-	05/16/00
	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00
	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00
	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00
	07/19/00	07/19/00	07/19/00	07/19/00	07/19/00	07/19/00	07/19/00
	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00
	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00
	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00
	09/19/00	09/19/00	09/19/00	-	09/19/00	09/19/00	09/19/00
	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	-
	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01
	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01
	05/29/01	05/29/01	05/29/01	05/29/01	05/29/01	05/29/01	05/29/01
	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01
	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01
	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	-
	08/08/01	08/08/01	-	08/08/01	-	-	08/08/01
	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	-
	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01
	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01
	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01
	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02
	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04
	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04
	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04
	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04
	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04
	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04
	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04
	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05
	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05
	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05
	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05
	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05
	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05
	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05

Station	Secchi	Turbidity	Total Suspended Solids	Dissolved Oxygen	Total Ammonia	Total Phosphorus	Chlorophyll *a*
OOL-1	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07
	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07
	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07
	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07
	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07
	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07
	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07
	04/15/08	04/15/08	04/15/08	04/15/08	04/15/08	04/15/08	04/15/08
	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08
	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08
	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08
	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08
	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08
	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08
OOL-2	04/18/00	04/18/00	04/18/00	-	04/18/00	04/18/00	04/18/00
	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00
	05/16/00	05/16/00	05/16/00	-	05/16/00	05/16/00	05/16/00
	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00
	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00
	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00
	07/19/00	-	07/19/00	-	07/19/00	07/19/00	07/19/00
	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00
	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00
	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00
	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00
	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	-
	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01
	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01
	05/29/01	-	05/29/01	-	05/29/01	05/29/01	05/29/01
	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01
	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01
	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	-
	08/08/01	08/08/01	-	08/08/01	-	-	-
	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	-
	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01
	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01
	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	-
	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02
	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04
	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04
	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04
	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04
	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04
	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04
	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04
	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05
	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05
	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05
	07/12/05	-	07/12/05	-	07/12/05	07/12/05	07/12/05
	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05
	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05
	10/11/05	10/11/050	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05
	04/10/07	4/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07
	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07
	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07

Station	Secchi	Turbidity	Total Suspended Solids	Dissolved Oxygen	Total Ammonia	Total Phosphorus	Chlorophyll *a*
OOL-2	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07
	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07
	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07
	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07
	04/15/08	04/15/08	04/15/08	04/15/08	04/15/08	04/15/08	04/15/08
	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08
	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08
	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08
	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08
	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08
	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08
OOL-3	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00
	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00
	05/16/00	-	05/16/00	-	05/16/00	05/16/00	05/16/00
	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00
	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00
	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00
	07/19/00	-	07/19/00	-	07/19/00	07/19/00	07/19/00
	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00
	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00
	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00
	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00
	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	-
	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01
	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01
	05/29/01	05/29/01	05/29/01	-	05/29/01	05/29/01	05/29/01
	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01
	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01
	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	-
	08/08/01	08/08/01	-	08/08/01	-	-	-
	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01
	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01
	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01
	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01
	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02
	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04
	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04
	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04
	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04
	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04
	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04
	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04
	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05
	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05
	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05
	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05
	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05
	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05
	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05
	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07
	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07
	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07
	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07	07/10/07
	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07
	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07

Station	Secchi	Turbidity	Total Suspended Solids	Dissolved Oxygen	Total Ammonia	Total Phosphorus	Chlorophyll *a*
OOL-3	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07
	-	-	-	-	-	-	-
	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08
	-	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08
	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08
	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08
	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08
	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08
OOL-4	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00
	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00
	05/16/00	-	05/16/00	-	05/16/00	05/16/00	05/16/00
	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00
	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00
	07/05/00	07/05/00	-	-	07/05/00	07/05/00	-
	07/19/00	07/19/00	-	-	07/19/00	07/19/00	07/19/00
	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00
	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00
	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00
	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00
	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	-
	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01
	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01
	-	-	-	-	-	-	-
	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01
	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01
	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	-
	-	-	-	-	-	-	-
	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	-
	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01
	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01
	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	-
	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02
	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04
	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04
	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04
	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04
	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04
	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04
	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04
	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05
	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05
	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05
	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05
	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05
	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05
	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05
	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07
	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07
	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07
	-	-	-	-	-	-	-
	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07
	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07
	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07
	-	-	-	-	-	-	-
	-	-	-	-	-	-	-

Station	Secchi	Turbidity	Total Suspended Solids	Dissolved Oxygen	Total Ammonia	Total Phosphorus	Chlorophyll *a*
OOL-4	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08
	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08
	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08
	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08
	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08
OOL-5	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00	04/18/00
	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00	05/02/00
	05/16/00	-	05/16/00	-	05/16/00	05/16/00	05/16/00
	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00	06/06/00
	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00	06/20/00
	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00	07/05/00
	07/19/00	-	07/19/00	-	07/19/00	07/19/00	07/19/00
	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00	08/01/00
	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00	08/15/00
	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00	09/06/00
	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00	09/19/00
	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	10/24/00	-
	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01	04/24/01
	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01	05/15/01
	-	-	-	-	-	-	-
	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01	06/19/01
	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01	07/17/01
	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	07/31/01	-
	-	-	-	-	-	-	-
	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	08/21/01	-
	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01	09/04/01
	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01	09/18/01
	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	10/23/01	-
	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02	10/22/02
	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04	04/13/04
	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04	05/11/04
	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04	06/15/04
	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04	07/13/04
	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04	08/10/04
	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04	09/14/04
	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04	10/13/04
	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05	04/12/05
	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05	05/10/05
	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05	06/14/05
	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05	07/12/05
	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05	08/16/05
	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05	09/12/05
	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05	10/11/05
	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07	04/10/07
	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07	05/16/07
	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07	06/12/07
	-	-	-	-	-	-	-
	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07	08/14/07
	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07	09/11/07
	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07	10/18/07
	-	-	-	-	-	-	-
	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08	05/13/08
	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08	06/11/08
	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08	07/08/08
	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08	08/12/08
	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08	09/09/08
	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08	10/15/08

Appendix 2. Raw data for Oologah Lake for the 2000 – 2008 study period.

Station	Date	Secchi (m)	Turbidity (NTU)	Total Suspended Solids (mg/l)	Dissolved Oxygen (mg/l)	Total Ammonia (mg/l)	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)
OOL-1	04/18/00	0.31	32.8	7.20	9.70	0.160	0.070	3.90
OOL-2	04/18/00	0.32	42.0	11.00	*	0.068	0.089	5.10
OOL-3	04/18/00	0.22	67.6	21.40	9.44	<0.06	0.112	6.60
OOL-4	04/18/00	0.20	80.1	31.20	9.62	0.110	0.131	13.20
OOL-5	04/18/00	0.19	79.7	56.00	10.08	<0.06	0.149	20.30
OOL-1	05/02/00	0.52	22.7	<4	8.80	0.220	0.050	1.80
OOL-2	05/02/00	0.41	25.4	8.20	9.09	<0.06	0.060	5.00
OOL-3	05/02/00	0.30	46.4	14.20	8.75	<0.06	0.080	7.70
OOL-4	05/02/00	0.22	55.3	26.00	8.66	<0.06	0.090	12.80
OOL-5	05/02/00	0.30	47.8	38.00	7.32	0.070	0.120	22.30
OOL-1	05/16/00	*	*	*	*	*	*	1.80
OOL-2	05/16/00	0.35	40.6	17.40	*	<0.06	0.427	2.00
OOL-3	05/16/00	0.20	*	29.00	*	0.079	0.203	2.10
OOL-4	05/16/00	0.20	*	68.30	*	0.100	0.322	1.90
OOL-5	05/16/00	0.15	*	83.00	*	0.170	0.495	2.70
OOL-1	06/06/00	0.58	18.2	15.80	12.67	0.100	0.035	13.10
OOL-2	06/06/00	0.37	31.7	10.60	10.07	<0.06	0.043	3.30
OOL-3	06/06/00	0.20	73.9	24.80	9.21	<0.06	0.060	3.90
OOL-4	06/06/00	0.12	115.6	61.10	9.74	<0.06	0.081	5.50
OOL-5	06/06/00	0.15	117.5	68.00	9.66	<0.06	0.083	11.30
OOL-1	06/20/00	0.42	30.9	7.23	7.28	<0.06	0.051	1.80
OOL-2	06/20/00	0.25	61.9	22.80	7.38	<0.06	0.072	1.30
OOL-3	06/20/00	0.25	63.3	37.40	7.71	<0.06	0.072	10.00
OOL-4	06/20/00	0.20	102.6	56.00	7.07	<0.06	0.137	6.40
OOL-5	06/20/00	0.12	181.0	102.00	7.44	0.069	0.148	3.40
OOL-1	07/05/00	0.61	26.8	<4	7.39	<0.06	0.057	3.90

Station	**Date**	**Secchi (m)**	**Turbidity (NTU)**	**Total Suspended Solids (mg/l)**	**Dissolved Oxygen (mg/l)**	**Total Ammonia (mg/l)**	**Total Phosphorus (mg/l)**	**Chlorophyll *a* (µg/l)**
OOL-2	07/05/00	0.31	50.7	12.00	6.81	<0.06	0.088	3.40
OOL-3	07/05/00	0.20	72.9	16.00	6.55	<0.06	0.114	3.60
OOL-4	07/05/00	0.15	*	36.00	*	<0.06	0.145	*
OOL-5	07/05/00	0.12	145.9	60.00	7.07	<0.06	0.179	3.60
OOL-1	07/19/00	0.90	13.3	<4	6.43	<0.06	0.053	2.20
OOL-2	07/19/00	0.20	*	5.60	*	0.098	0.058	5.70
OOL-3	07/19/00	0.60	*	7.20	*	0.110	0.067	4.80
OOL-4	07/19/00	0.35	*	14.80	*	0.100	0.078	3.50
OOL-5	07/19/00	0.28	*	37.10	*	0.200	0.086	15.60
OOL-1	08/01/00	0.58	13.3	7.80	8.84	<0.06	0.041	21.50
OOL-2	08/01/00	0.55	19.6	5.30	8.86	<0.06	0.056	13.70
OOL-3	08/01/00	0.62	30.7	9.60	8.34	<0.06	0.049	10.80
OOL-4	08/01/00	0.55	17.0	13.70	10.58	<0.06	0.072	28.80
OOL-5	08/01/00	0.35	45.5	33.60	7.51	<0.06	0.133	43.10
OOL-1	08/15/00	0.80	11.7	<4	6.12	<0.06	0.041	2.20
OOL-2	08/15/00	0.72	14.2	7.56	7.91	<0.06	0.044	10.70
OOL-3	08/15/00	0.60	21.8	12.70	7.73	<0.06	0.052	9.80
OOL-4	08/15/00	0.45	42.4	12.30	6.78	<0.06	0.088	8.60
OOL-5	08/15/00	0.30	82.5	67.00	7.02	<0.06	0.156	42.50
OOL-1	09/06/00	0.88	8.4	6.40	8.41	0.029	0.042	11.60
OOL-2	09/06/00	0.40	27.0	13.00	5.90	0.039	0.073	7.50
OOL-3	09/06/00	0.38	31.8	16.00	5.89	0.059	0.078	4.10
OOL-4	09/06/00	0.24	53.0	30.00	6.04	0.096	0.100	9.30
OOL-5	09/06/00	0.21	91.5	77.00	6.18	0.071	0.190	23.30
OOL-1	09/19/00	0.68	13.0	6.50	*	0.043	0.078	1.30
OOL-2	09/19/00	0.41	27.9	10.00	6.60	0.034	0.093	3.40
OOL-3	09/19/00	0.32	38.5	24.00	7.17	0.043	0.094	9.20

Station	Date	Secchi (m)	Turbidity (NTU)	Total Suspended Solids (mg/l)	Dissolved Oxygen (mg/l)	Total Ammonia (mg/l)	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)
OOL-4	09/19/00	0.23	81.7	40.00	6.97	0.045	0.160	11.00
OOL-5	09/19/00	0.10	208.5	170.00	7.42	0.033	0.390	26.20
OOL-1	10/24/00	0.60	16.0	<4	9.23	0.049	0.079	*
OOL-2	10/24/00	0.48	20.1	7.00	9.76	<0.023	0.078	*
OOL-3	10/24/00	0.31	95.3	11.00	9.41	<0.023	0.098	*
OOL-4	10/24/00	0.20	54.3	19.00	8.97	0.028	0.130	*
OOL-5	10/24/00	0.18	126.5	84.00	9.42	0.033	0.260	*
OOL-1	04/24/01	0.39	49.5	6.10	9.13	<0.05	0.092	2.00
OOL-2	04/24/01	0.28	79.3	24.00	9.11	0.120	0.120	1.70
OOL-3	04/24/01	0.22	89.8	31.00	9.05	0.084	0.130	1.90
OOL-4	04/24/01	0.18	118.5	55.00	8.73	<0.05	0.160	2.60
OOL-5	04/24/01	0.11	147.9	67.00	8.61	0.057	0.190	6.60
OOL-1	05/15/01	0.35	48.5	6.40	7.29	<0.05	0.095	3.00
OOL-2	05/15/01	0.38	52.1	10.00	7.69	<0.05	0.088	4.60
OOL-3	05/15/01	0.35	59.7	19.00	7.54	<0.05	0.100	3.90
OOL-4	05/15/01	0.27	89.6	48.00	7.08	0.380	0.130	5.60
OOL-5	05/15/01	0.15	179.3	40.00	7.35	<0.05	0.220	15.50
OOL-1	05/29/01	0.50	31.4	12.00	7.87	<0.05	0.064	3.30
OOL-2	05/29/01	0.45	*	11.00	*	<0.05	0.065	2.50
OOL-3	05/29/01	0.42	16.0	10.00	*	<0.05	0.061	3.90
OOL-1	06/19/01	0.72	18.5	<4	7.31	0.052	0.052	1.40
OOL-2	06/19/01	0.52	27.1	<4	8.16	0.051	0.076	12.50
OOL-3	06/19/01	0.38	31.1	16.00	7.86	<0.05	0.060	9.60
OOL-4	06/19/01	0.22	79.9	33.00	7.19	0.056	0.100	8.60
OOL-5	06/19/01	0.09	203.7	130.00	6.87	0.086	0.280	11.20
OOL-1	07/17/01	0.58	16.4	6.10	6.74	0.520	0.035	3.00
OOL-2	07/17/01	0.40	26.3	15.00	7.21	0.058	0.047	5.90

Station	**Date**	**Secchi (m)**	**Turbidity (NTU)**	**Total Suspended Solids (mg/l)**	**Dissolved Oxygen (mg/l)**	**Total Ammonia (mg/l)**	**Total Phosphorus (mg/l)**	**Chlorophyll *a* (µg/l)**
OOL-3	07/17/01	0.25	50.0	25.00	7.81	0.055	0.077	7.20
OOL-4	07/17/01	0.15	92.3	63.00	7.49	0.130	0.160	13.70
OOL-5	07/17/01	0.15	282.1	220.00	7.46	0.120	0.300	25.60
OOL-1	07/31/01	0.96	10.5	4.00	6.40	<0.05	0.020	*
OOL-2	07/31/01	0.95	11.3	7.10	8.03	<0.05	0.025	*
OOL-3	07/31/01	0.45	27.5	16.00	7.14	<0.05	0.043	*
OOL-4	07/31/01	0.42	56.0	32.00	6.58	<0.05	0.094	*
OOL-5	07/31/01	0.15	140.0	110.00	6.69	<0.05	0.180	*
OOL-1	08/08/01	1.40	4.1	*	9.33	*	*	3.20
OOL-2	08/08/01	0.90	6.9	*	9.23	*	*	*
OOL-3	08/08/01	0.45	21.5	*	7.44	*	*	*
OOL-1	08/21/01	0.80	9.8	6.60	5.49	0.140	0.035	*
OOL-2	08/21/01	0.72	13.0	8.20	7.03	<0.05	0.038	*
OOL-3	08/21/01	0.40	26.9	15.00	7.01	0.150	0.056	*
OOL-4	08/21/01	0.24	62.2	39.00	6.64	0.150	0.110	*
OOL-5	08/21/01	0.18	92.4	68.00	7.10	0.100	0.180	*
OOL-1	09/04/01	1.05	8.0	7.70	8.65	<0.05	0.036	12.30
OOL-2	09/04/01	1.15	17.6	7.10	7.68	<0.05	0.031	6.90
OOL-3	09/04/01	0.75	12.5	7.70	6.95	0.078	0.040	4.30
OOL-4	09/04/01	0.35	24.2	15.00	7.60	<0.05	0.055	9.50
OOL-5	09/04/01	0.25	60.6	22.00	6.96	0.180	0.059	12.70
OOL-1	09/18/01	1.00	12.9	5.80	6.09	<0.05	0.048	1.20
OOL-2	09/18/01	0.81	15.9	17.00	7.25	<0.05	0.052	6.70
OOL-3	09/18/01	0.58	29.0	17.00	7.25	<0.05	0.075	6.90
OOL-4	09/18/01	0.37	66.5	48.00	7.14	0.076	0.150	11.30
OOL-5	09/18/01	0.24	102.3	78.00	7.74	0.059	0.200	22.20
OOL-1	10/23/01	0.68	14.6	8.50	8.93	<0.05	0.046	3.70

Station	Date	Secchi (m)	Turbidity (NTU)	Total Suspended Solids (mg/l)	Dissolved Oxygen (mg/l)	Total Ammonia (mg/l)	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)
OOL-2	10/23/01	0.05	18.6	9.80	9.39	<0.05	0.053	*
OOL-4	10/23/01	0.18	85.9	49.00	9.16	0.089	0.130	*
OOL-5	10/23/01	0.13	127.9	96.00	8.72	0.360	0.170	*
OOL-1	10/22/02	0.95	6.8	4.80	8.83	<0.030	0.044	5.60
OOL-2	10/22/02	0.65	7.6	5.80	8.96	0.041	0.044	7.70
OOL-3	10/22/02	0.42	17.3	9.00	8.91	0.042	0.059	6.60
OOL-4	10/22/02	0.35	22.5	17.00	9.86	0.053	0.070	13.40
OOL-5	10/22/02	0.22	26.5	22.00	9.53	<0.030	0.075	15.00
OOL-1	04/13/04	0.31	37.2	17.00	9.68	0.045	0.094	3.80
OOL-2	04/13/04	0.28	45.1	21.00	9.60	<0.038	0.087	5.60
OOL-3	04/13/04	0.35	42.9	19.00	9.82	0.055	0.078	9.10
OOL-4	04/13/04	0.21	42.0	40.00	10.23	0.052	0.084	17.50
OOL-5	04/13/04	0.23	38.0	38.00	10.81	<0.038	0.110	31.70
OOL-1	05/11/04	0.60	20.5	4.80	8.84	<0.038	0.068	1.50
OOL-2	05/11/04	0.60	35.5	7.80	8.41	<0.038	0.096	1.40
OOL-3	05/11/04	0.40	39.5	6.80	8.37	<0.038	0.110	2.60
OOL-4	05/11/04	0.30	44.3	22.00	8.07	<0.038	0.120	5.80
OOL-5	05/11/04	0.25	52.1	48.00	8.00	<0.038	0.200	9.30
OOL-1	06/15/04	0.52	20.8	4.80	7.50	<0.038	0.071	2.10
OOL-2	06/15/04	0.47	27.9	8.40	7.81	<0.038	0.082	4.50
OOL-3	06/15/04	0.38	35.3	19.00	7.61	<0.038	0.110	5.50
OOL-4	06/15/04	0.35	49.5	36.00	7.14	<0.038	0.100	5.60
OOL-5	06/15/04	0.10	146.7	160.00	6.30	0.053	0.150	11.50
OOL-1	07/13/04	0.62	14.5	7.00	6.15	<0.038	0.096	1.60
OOL-2	07/13/04	0.64	15.0	11.00	7.86	<0.038	0.061	8.60
OOL-3	07/13/04	0.47	20.6	14.00	7.49	<0.038	0.083	18.60
OOL-4	07/13/04	0.31	39.0	28.00	6.87	<0.038	0.120	8.60

Station	**Date**	**Secchi (m)**	**Turbidity (NTU)**	**Total Suspended Solids (mg/l)**	**Dissolved Oxygen (mg/l)**	**Total Ammonia (mg/l)**	**Total Phosphorus (mg/l)**	**Chlorophyll *a* (µg/l)**
OOL-5	07/13/04	0.23	62.1	52.00	6.85	<0.038	0.160	8.80
OOL-1	08/10/04	1.10	6.7	3.20	7.66	<0.038	0.040	10.90
OOL-2	08/10/04	0.99	6.8	5.40	9.92	<0.038	0.440	26.40
OOL-3	08/10/04	0.80	8.9	9.10	9.63	<0.038	0.056	36.00
OOL-4	08/10/04	0.62	15.5	9.20	7.29	<0.038	0.055	16.60
OOL-5	08/10/04	0.43	18.4	20.00	8.43	<0.038	0.170	60.20
OOL-1	09/14/04	0.93	7.7	4.20	6.79	<0.038	0.050	2.00
OOL-2	09/14/04	0.72	8.7	5.60	7.96	<0.038	0.048	7.10
OOL-3	09/14/04	0.53	12.8	12.00	7.91	<0.038	0.064	12.10
OOL-4	09/14/04	0.30	30.0	32.00	7.35	<0.038	0.120	14.00
OOL-5	09/14/04	0.10	370.9	160.00	7.41	<0.038	0.340	17.60
OOL-1	10/13/04	1.11	7.3	3.40	8.37	<0.038	0.045	2.50
OOL-2	10/13/04	0.81	10.7	7.70	8.67	<0.038	0.065	5.30
OOL-3	10/13/04	0.48	16.5	14.00	9.05	<0.038	0.079	11.40
OOL-4	10/13/04	0.40	24.5	20.00	9.52	<0.038	0.087	12.00
OOL-5	10/13/04	0.32	38.9	43.00	9.57	<0.038	0.120	12.80
OOL-1	04/12/05	0.98	10.4	6.40	9.90	0.031	0.073	1.20
OOL-2	04/12/05	0.68	16.7	12.00	9.56	0.063	0.062	1.90
OOL-3	04/12/05	0.41	40.8	32.00	9.19	0.073	0.077	3.70
OOL-4	04/12/05	0.33	57.1	62.00	9.16	0.066	0.094	6.40
OOL-5	04/12/05	0.32	79.7	98.00	8.90	0.054	0.085	8.00
OOL-1	05/10/05	1.20	5.9	3.60	9.39	<0.030	0.043	2.00
OOL-2	05/10/05	0.90	7.1	8.60	9.76	<0.030	0.049	4.70
OOL-3	05/10/05	0.75	11.2	8.60	9.79	<0.030	0.053	7.30
OOL-4	05/10/05	0.35	23.9	28.00	8.96	<0.030	0.084	7.20
OOL-5	05/10/05	0.17	67.6	85.00	8.70	<0.030	0.190	32.10
OOL-1	06/14/05	1.51	3.7	4.40	8.23	<0.030	0.020	4.60

Station	Date	Secchi (m)	Turbidity (NTU)	Total Suspended Solids (mg/l)	Dissolved Oxygen (mg/l)	Total Ammonia (mg/l)	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)
OOL-2	06/14/05	0.60	17.8	13.00	7.73	<0.030	0.060	10.40
OOL-3	06/14/05	0.23	60.5	47.00	6.66	<0.030	0.180	6.40
OOL-4	06/14/05	0.19	78.3	68.00	6.41	<0.030	0.220	6.80
OOL-5	06/14/05	0.18	94.1	72.00	5.51	0.039	0.240	6.50
OOL-1	07/12/05	1.55	3.2	4.50	9.04	0.034	0.040	8.60
OOL-2	07/12/05	1.10	*	7.50	*	<0.030	0.160	10.10
OOL-3	07/12/05	1.02	5.4	5.50	9.07	<0.030	0.062	7.60
OOL-4	07/12/05	0.98	8.2	8.00	8.42	0.032	0.290	9.00
OOL-5	07/12/05	0.60	22.2	16.00	7.27	<0.030	0.290	15.10
OOL-1	08/16/05	1.40	5.3	3.40	5.12	<0.050	0.076	2.40
OOL-2	08/16/05	1.10	7.6	7.80	6.72	<0.050	0.040	6.20
OOL-3	08/16/05	0.81	9.8	10.00	7.22	<0.050	0.044	9.80
OOL-4	08/16/05	0.39	30.1	23.00	6.38	0.061	0.096	6.10
OOL-5	08/16/05	0.21	97.2	58.00	6.93	0.096	0.081	25.30
OOL-1	09/12/05	1.10	8.8	3.20	5.60	<0.050	0.059	1.80
OOL-2	09/12/05	0.72	13.2	6.60	6.36	<0.050	0.070	4.50
OOL-3	09/12/05	0.55	33.6	15.00	6.70	<0.050	0.098	6.00
OOL-4	09/12/05	0.19	72.0	69.00	7.23	<0.050	0.160	5.10
OOL-5	09/12/05	0.19	74.6	73.00	7.53	<0.050	0.180	4.80
OOL-1	10/11/05	1.10	6.8	8.00	8.01	<0.050	0.055	2.20
OOL-2	10/11/05	0.50	9.5	10.00	8.98	<0.050	0.072	6.20
OOL-3	10/11/05	0.52	18.1	12.00	8.67	<0.050	0.070	2.50
OOL-4	10/11/05	0.25	36.1	33.00	9.14	<0.050	0.130	11.30
OOL-5	10/11/05	0.19	47.6	44.00	9.44	<0.050	0.120	16.10
OOL-1	04/10/07	0.75	9.6	6.00	9.33	<0.10	0.029	1.40
OOL-2	04/10/07	0.45	22.8	7.20	9.13	<0.10	0.056	0.80
OOL-3	04/10/07	0.20	40.1	15.00	9.56	<0.10	0.073	1.10

Station	**Date**	**Secchi (m)**	**Turbidity (NTU)**	**Total Suspended Solids (mg/l)**	**Dissolved Oxygen (mg/l)**	**Total Ammonia (mg/l)**	**Total Phosphorus (mg/l)**	**Chlorophyll *a* (µg/l)**
OOL-5	04/10/07	0.15	57.2	57.00	9.12	<0.10	0.090	3.00
OOL-1	05/16/07	0.45	21.9	6.00	6.75	<0.10	0.100	2.80
OOL-2	05/16/07	0.39	29.7	20.00	6.47	<0.10	0.110	3.40
OOL-3	05/16/07	0.25	34.0	16.00	4.89	<0.10	0.140	3.40
OOL-4	05/16/07	0.33	44.8	21.00	4.16	<0.10	0.170	0.80
OOL-5	05/16/07	0.35	36.5	17.00	5.89	<0.10	0.170	5.90
OOL-1	06/12/07	0.69	13.2	5.20	7.28	<0.10	0.086	1.40
OOL-2	06/12/07	0.48	17.8	6.20	7.01	<0.10	0.110	1.00
OOL-3	06/12/07	0.38	27.6	14.00	6.67	<0.10	0.110	1.80
OOL-4	06/12/07	0.22	54.1	36.00	6.83	<0.10	0.160	2.60
OOL-5	06/12/07	0.15	94.5	87.00	5.95	<0.10	0.210	<0.1
OOL-1	07/10/07	0.35	31.0	8.00	3.87	<0.10	0.110	3.20
OOL-2	07/10/07	0.45	23.5	5.60	5.64	<0.10	0.090	5.80
OOL-3	07/10/07	0.45	29.0	9.60	5.50	<0.10	0.110	5.10
OOL-1	08/14/07	1.65	-0.8	3.40	9.11	<0.10	0.027	6.50
OOL-2	08/14/07	1.46	-0.4	4.60	9.53	<0.10	0.030	8.70
OOL-3	08/14/07	1.29	0.1	3.80	9.71	<0.10	0.027	6.90
OOL-4	08/14/07	1.18	1.9	5.60	9.25	0.120	0.037	11.00
OOL-5	08/14/07	0.85	5.1	8.60	9.32	0.140	0.033	9.30
OOL-1	09/11/07	0.79	9.7	6.00	6.19	<0.10	0.081	2.40
OOL-2	09/11/07	0.49	14.5	13.00	6.62	<0.10	0.092	2.50
OOL-3	09/11/07	0.45	18.5	31.00	6.91	<0.10	0.110	2.40
OOL-4	09/11/07	0.45	23.2	31.00	6.91	<0.10	0.120	2.30
OOL-5	09/11/07	0.21	54.9	58.00	7.07	<0.10	0.160	6.30
OOL-1	10/18/07	0.90	5.9	4.80	7.77	<0.10	0.063	0.90
OOL-2	10/18/07	0.65	9.2	10.00	8.43	<0.10	0.073	5.90
OOL-3	10/18/07	0.65	10.0	11.00	8.59	<0.10	0.071	7.10

Station	Date	Secchi (m)	Turbidity (NTU)	Total Suspended Solids (mg/l)	Dissolved Oxygen (mg/l)	Total Ammonia (mg/l)	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)
OOL-4	10/18/07	0.35	24.5	29.00	8.49	<0.10	0.096	14.60
OOL-5	10/18/07	0.15	60.1	77.00	8.77	<0.10	0.180	22.80
OOL-1	04/15/08	0.55	13.9	6.60	10.50	<0.10	0.053	8.40
OOL-2	04/15/08	0.45	21.7	15.00	10.28	<0.10	0.077	8.20
OOL-1	05/13/08	0.60	20.3	6.00	8.33	<0.10	0.079	2.40
OOL-2	05/13/08	0.50	30.7	12.00	8.11	<0.10	0.100	2.30
OOL-3	05/13/08	0.30	56.7	24.00	7.87	<0.10	0.140	2.70
OOL-5	05/13/08	0.20	68.0	39.00	8.00	0.110	0.160	2.20
OOL-1	06/11/08	0.23	53.4	5.70	6.28	<0.10	0.130	2.90
OOL-2	06/11/08	0.15	68.0	5.70	7.22	<0.10	0.140	1.20
OOL-3	06/11/08	*	74.1	11.00	7.07	<0.10	0.180	1.30
OOL-4	06/11/08	0.18	63.4	41.00	6.97	<0.10	0.180	2.40
OOL-5	06/11/08	0.15	64.6	31.00	7.20	<0.10	0.190	1.20
OOL-1	07/08/08	0.48	19.6	2.80	6.54	<0.10	0.087	4.30
OOL-2	07/08/08	0.48	20.2	6.80	6.85	<0.10	0.093	9.00
OOL-3	07/08/08	0.45	22.3	6.80	6.84	<0.10	0.096	7.10
OOL-4	07/08/08	0.25	30.9	18.00	6.50	<0.10	0.092	15.90
OOL-5	07/08/08	0.20	34.2	22.00	6.87	<0.10	0.110	13.00
OOL-1	08/12/08	0.68	8.0	5.20	5.96	<0.10	0.050	5.90
OOL-2	08/12/08	0.58	12.7	7.80	5.82	<0.10	0.083	6.50
OOL-3	08/12/08	0.39	25.1	16.00	6.00	<0.10	0.100	6.10
OOL-4	08/12/08	0.25	113.3	73.00	5.67	0.140	0.250	6.60
OOL-5	08/12/08	0.15	150.8	130.00	5.47	<0.10	0.330	2.00
OOL-1	09/09/08	0.80	9.9	4.80	7.42	<0.10	0.077	4.10
OOL-2	09/09/08	0.50	24.3	13.00	7.13	<0.10	0.110	4.70
OOL-3	09/09/08	0.37	37.4	16.00	7.21	<0.10	0.130	4.60

Station	Date	Secchi (m)	Turbidity (NTU)	Total Suspended Solids (mg/l)	Dissolved Oxygen (mg/l)	Total Ammonia (mg/l)	Total Phosphorus (mg/l)	Chlorophyll *a* (µg/l)
OOL-4	09/09/08	0.22	58.3	70.00	7.27	<0.10	0.160	6.10
OOL-5	09/09/08	0.15	70.5	74.00	6.96	<0.10	0.200	10.60
OOL-1	10/15/08	0.87	9.6	5.00	7.36	<0.10	0.064	6.00
OOL-2	10/15/08	0.65	15.8	8.80	8.03	<0.10	0.085	8.30
OOL-3	10/15/08	0.56	20.9	11.00	8.15	<0.10	0.090	8.50

Appendix 3. Hydraulic Residence Time results by sample date for Oologah Lake during the 2000 – 2008 study period.

Date	HRT (days)	Date	HRT (days)
04/18/00	63.2	6/15/04	43.0
05/02/00	154.8	07/13/04	107.8
05/16/00	125.8	08/10/04	68.6
06/06/00	82.1	09/14/04	4368.9
06/20/00	349.3	10/13/04	46831.9
07/05/00	56.0	04/12/05	120.4
07/19/00	40.4	05/10/05	306.6
08/01/00	50.1	06/14/05	106.3
08/15/00	179.3	07/12/05	33.9
09/06/00	8357.1	08/16/05	193.9
09/19/00	7869.0	09/12/05	90.1
10/24/00	5930.1	10/11/05	93.6
04/24/01	126.9	04/10/07	210.4
05/15/01	246.1	05/16/07	48.8
05/29/01	474.7	06/12/07	33.7
06/19/01	192.4	07/10/07	34.6
07/17/01	74.0	08/14/07	23.6
07/31/01	348.8	09/11/07	87.4
08/08/01	5260.8	10/18/07	4530.8
08/21/01	6341.3	04/15/08	115.1
09/04/01	5421.7	05/13/08	42.5
09/18/01	16191.7	06/11/08	26.2
10/23/01	842.0	07/08/08	28.0
10/22/02	5368207.4	08/12/08	49.9
4/13/04	37.7	09/09/08	43.8
05/11/04	77.4	10/15/08	47.2

VITA

Tonya Nicole Dunn

Candidate for the Degree of

Master of Science

Thesis: ANALYSIS OF WATER CLARITY, DISSOLVED OXYGEN, TOTAL AMMONIA, TOTAL PHOSPHORUS, AND CHLOROPHYLL *a* OF OOLOGAH LAKE, OKLAHOMA, AFTER ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) INVASION

Major Field: Environmental Science

Biographical:

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I completed the requirements for the Master of Science in Environmental Science with a Water and Watershed Management Emphasis at Oklahoma State University, Stillwater, Oklahoma in May, 2011.

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Name: Tonya Nicole Dunn Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: ANALYSIS OF WATER CLARITY, DISSOLVED OXYGEN, TOTAL AMMONIA, TOTAL PHOSPHORUS, AND CHLOROPHYLL *a* OF OOLOGAH LAKE, OKLAHOMA, AFTER ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) INVASION

Pages in Study: 126 Candidate for the Degree of Master of Science

Major Field: Environmental Science

Scope and Method of Study: Oologah Lake, in Oklahoma, is a U.S. Army Corps of Engineers project; flows are controlled by dam releases for navigation and flood control purposes. Zebra mussels were discovered in Oologah Lake in June of 2003. Monthly water quality samples were taken at five stations within the lake for nine consecutive years (2000 – 2008). This data set allowed for analysis of the lake's water quality parameters pre- and post-zebra mussel invasion. Water samples were analyzed for Secchi depth, turbidity, total suspended solids, dissolved oxygen, total phosphorus, total ammonia, and chlorophyll *a* concentrations. Standard procedures and a YSI sonde unit were used to measure Secchi depth, dissolved oxygen and turbidity at each station; the other water quality parameters were measured using EPA and Standard Method procedures in the lab. Results for each parameter were analyzed using Analysis of Covariance (ANCOVA), significance determined at α=0.05, for lake-wide results and individual sampling stations. Hydraulic residence time was calculated for each sampling trip and used as the covariate in the ANCOVA. During the study period, three levels of treatment periods were used, before zebra mussel arrival, during zebra mussel presence, and after the zebra mussel die-off, which occurred in 2006.

Findings and Conclusions: ANCOVA results indicate that there were no significant differences between treatment means (*Before*, *During*, and *After* zebra mussels presence) in water clarity measurements, dissolved oxygen, total phosphorus, or chlorophyll *a* concentrations for the lake-wide analysis. There was, however, a significant difference between treatment means seen at individual sampling stations for total phosphorus, dissolved oxygen, and chlorophyll *a* concentration levels at individual sites (OOL-1, OOL-3, and OOL-5, respectively). Using hydraulic resident time as a covariate in this analysis helped to isolate the impacts that zebra mussels had on the system by accounting for the impact that Oologah Lake's hydrology has on each water quality parameter measurement. Proximity of water quality sampling station to the zebra mussel population location may be another factor in lack of direct impacts on Oologah Lake's water quality parameter concentrations.

ADVISER'S APPROVAL: Dr. Kevin Gustavson