# Changes in nearshore water quality from 1995 to 2014 and associated linkages to septic systems in Higgins Lake, MI

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## Executive Summary

This report presents a new water quality dataset for Higgins Lake, mostly collected in 2014, along with an analysis of these data relative to prior water quality data collected by the USGS, and human wastewater systems around the lake. Samples were collected at 21 sites in the near shore region of the lake, including some sites that overlapped USGS sampling sites collected in the late 1990s. Four sampling events were conducted throughout the summer and early fall of 2014. A single partial early-morning shoreline dissolved oxygen and specific conductivity survey was also conducted.

A primary product of this report is a new and more in-depth analysis of data collected by the USGS spanning 1995-2000 (select sites were also sampled in 2007), alongside a similar analysis of newly collected data from this study's 2014 sampling. This analysis highlights trends in water quality parameters, specifically those related to a major transition in wastewater treatment on the lake: the installation of a community wastewater treatment plant in 2009 for Camp Curnalia in the NW corner of the north basin of the lake.

Four datasets are analyzed in detail: total phosphorus (TP), nitrate+nitrite ($NO_3+NO_2$), specific conductivity, and boron (B). No significant temporal variations in concentrations were detected within the 2014 sampling period, thereby providing no support to the hypothesis that water quality is negatively impacted near the busy July 4th holiday. Comparing 2014 values to those from the late 1990s dataset showed a significant increase in near-shore surface water TP, which is of particular concern as the average concentration now exceeds the 12 ug/L mesotrophic threshold, where significant ecological changes begin to occur in the nearshore region lake. Specific conductivity values have steadily risen, indicating increased pollutant loads to the lake.

Temporal trends and spatial patterns in these data all support the hypothesis that the Camp Curnalia wastewater treatment plant has substantially improved water quality in the adjacent nearshore area, particularly due to groundwater inputs. Near Camp

Curnalia at paired USGS/MSU sites, TP concentrations in groundwater have greatly decreased, and $NO_3+NO_2$ concentrations dropped below detection limits. B, an indicator of septic system inputs, also exhibited a significant decline in concentration. In addition, specific conductivity in the Camp Curnalia area was the lowest in the partial shoreline survey.

Statistical modeling was used to relate sampled concentrations of these and other water quality constituents to measures of septic system density and groundwater influx. These models support that groundwater is a significant source of nutrients to the lake. Groundwater flow velocity into the lake, measured using a point-based seepage velocimeter, was the most significant variable explaining concentration patterns, while combinations of hydraulic gradient (how much slope there is in the water table near the lake) and septic/parcel density were also important.

## Contents

# Introduction

   Higgins Lake is Michigan's 10th largest inland lake, and one of its deepest. Despite its long history of clean water, Higgins Lake is experiencing ecological changes in water quality, underwater vegetation, invasive species, and Swimmer's Itch. Many of these changes impact the shallow region near shore, in the area called the shelf. Water quality monitoring programs such as the Cooperative Lakes Monitoring Program typically focus on the deeper areas of lakes. Measurements taken in those deeper areas do not always reflect the same character as shallower regions of a lake. This mismatch between deep water and shallow water characteristics can mask undesirable changes in water quality during a critical period when they could otherwise be mitigated.

   A large shallow shelf, characteristic of Higgins Lake, limits mixing of near-shore waters with deeper basin waters, particular during calm periods. According to a 2001 USGS report (Minnerick, 2001) and work conducted by this team during the summer of 2012, this leads to concentrations of nitrogen and phosphorous that are orders of magnitude higher in shelf water than in the deeper basins. Because the majority of the Higgins Lake shoreline is populated by septic-served homes, these septic systems may serve as a major source of nutrient contamination into the nearshore areas, particularly during the summer when seasonal homes are occupied.

   This study was designed as a follow-on to the 1995-1999 USGS study of nearshore waters to investigate current conditions with reference to shoreline human impacts, specifically septic systems. We: 1) collected water quality samples at 21 sampling locations around the perimeter of Higgins Lake; 2) analyzed this new dataset alongside the complete (and largely unpublished) USGS dataset; 3) characterized

septic systems around the lake using geographic information systems, high-resolution sampling and tracking chemical markers; and, 4) investigated linkages between septic systems and nutrients as the base of the swimmers-itch food web. We are also particularly interested in quantifying the potential impacts of the Camp Curnalia sewer system installation, which in 2009 rerouted household waste along the NW section of the North Basin out of septic systems and into a single community wastewater treatment system. Results from our study can also be used as a baseline for future work using other chemical fingerprints not typically collected in traditional water quality surveys.

# 2014 Study Design

## Sites and sampling

Water quality samples were collected from both the surface and subsurface (groundwater) at 21 established sites around the perimeter of Higgins Lake. These sites were chosen to provide spatial coverage of the entire shoreline, capturing variability in shoreline characteristics. Several of the sites were located near USGS recorded sites (Figure 1).
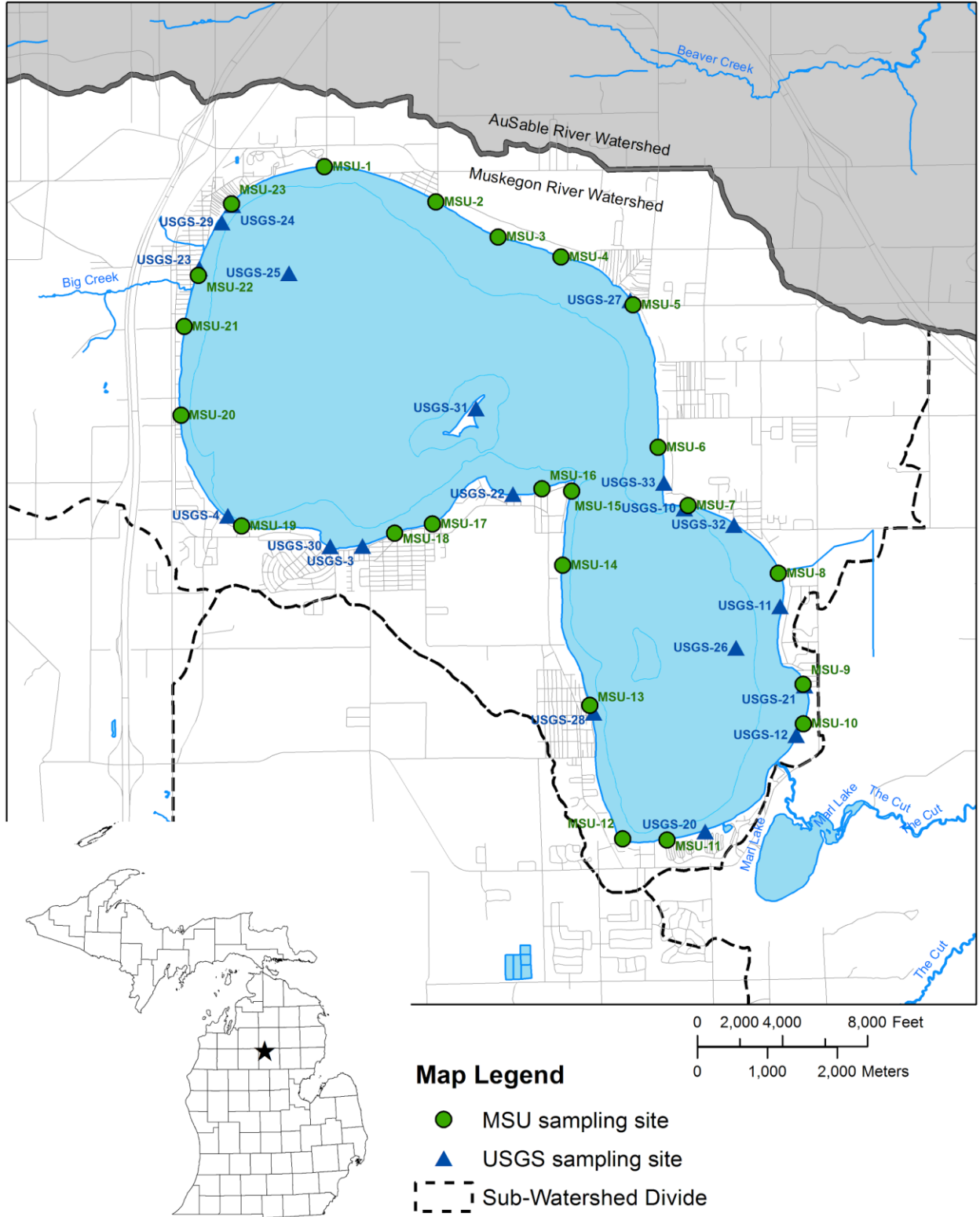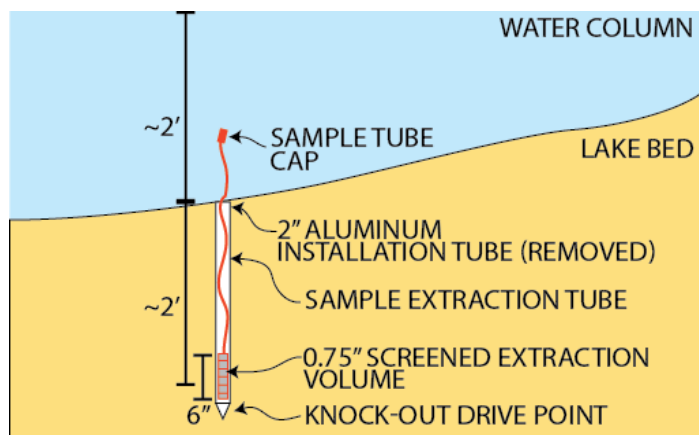
*Figure 1.* Map of Higgins Lake showing location of MSU and USGS water sampling sites. Ten foot bathymetric contour (light blue line) shows approximate shelf area.

Groundwater samples were collected from installed piezometers at each site. Sites were located close to the shoreline in shallow water (2 ft depth), and piezometers were installed to 2 ft below the lake bottom (Figure 2). Installations were completed in June 2014 and allowed to equilibrate several days prior to the first sampling (Table 1). Surface water samples were collected from the lake at each site in conjunction with groundwater sampling. All samples were collected via a peristaltic pump using a low-flow flow cell. Precautions were used to ensure that surface water was not forced into the lake sediments during groundwater sampling (data not shown).



*Figure 2.* Cross-sectional drawing of site showing SW and GW sample locations

Dissolved oxygen, temperature, pH, and specific conductivity were measured using an InSitu smarTROLL multi-paramater water quality probe. Groundwater and surface water samples were collected and analyzed for: Alkalinity, calcium (Ca), chloride (Cl), potassium (K), magnesium (Mg), nitrate-nitrite ($NO_3+NO_2$), ammonium ($NH_3$), sodium (Na), sulfate ($SO_4$), and elemental lithium (Li), boron (B), iron (Fe), zinc, (Zn), arsenic (As), cadmium (Cd), and lead (Pb).

*Table 1.* Site installation and sample collections.

| Activity | Date |
|---|---|
| Installation | June 5-12, 2014 |
| 1st Sampling | June 25-July 2, 2014 |
| 2nd Sampling | July 14-16, 2014 |
| 3rd Sampling | August 26-28, 2014 |
| 4th Sampling | October 15-17, 2014 |

## Measuring groundwater input

We measured groundwater inflow to the lake at each of our installed sites using a seepage meter following dye displacement methods (Koopmans & Berg, 2011). This method is a low-cost approach to measuring groundwater input and can be widely used. Briefly, we constructed the seepage meter out of a modified 5-gallon bucket and clear vinyl tubing. The seepage meter was pushed into sediment and allowed to equilibrate after installation for 30 minutes prior to injecting dye. After equilibration, ~5 mL of Rhodamine dye was injected into the tube at a known location. The location of

the leading edge of the dye was measured at 5, 10, and 15 minutes after dye injection. Figure 3 shows the seepage meter installation and dye injection. Average flow rate was calculated from the 3 time intervals and accounted for seepage meter dimensions. A corrected groundwater velocity is calculated by dividing the seepage rate by the porosity of the lake bottom sediment. This study area is dominated by glacial outwash sand and gravel with a representative porosity of 0.3. Measurements presented below were made in August 2014 (Figure 4).
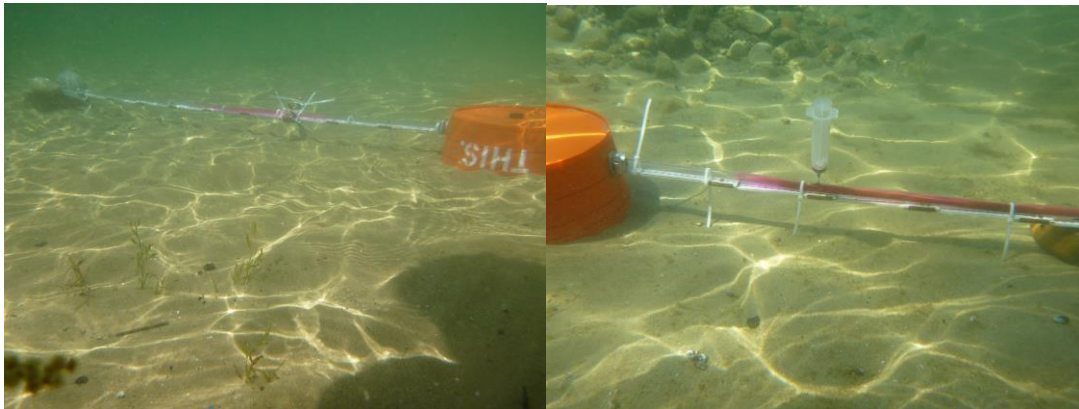


**Figure 3.** *Underwater photographs showing seepage meter installation (left) and a close-up of Rhodamine dye injection.*
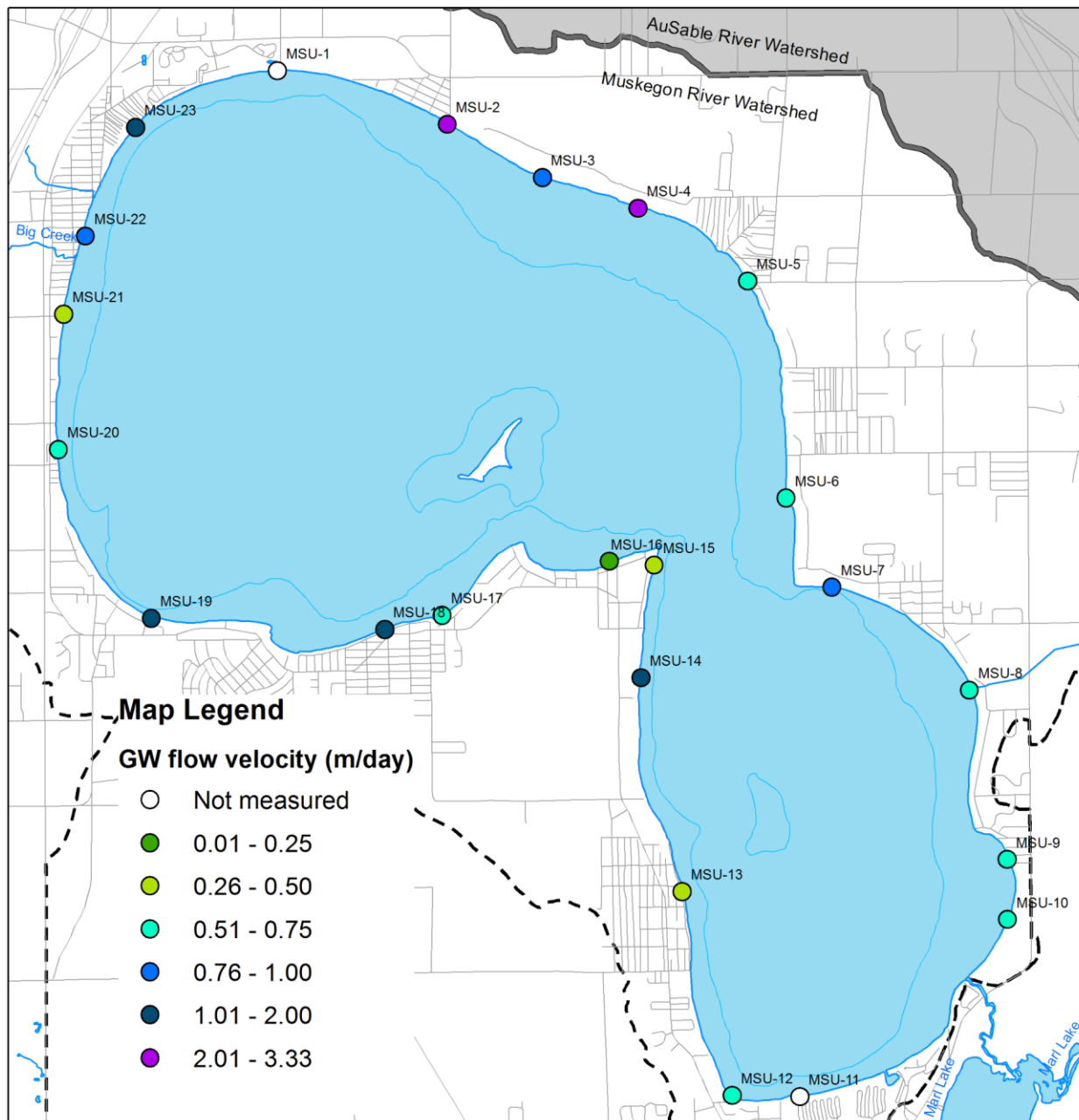
**Figure 4.** *Map of measured groundwater flow velocities from seepage meters.*

All of the sites have high groundwater flow into the lake according to USGS standards, over approximately 1 foot per day (0.3 m/day) (*Sustainability of Ground-Water Resources--Circular 1186*). The slowest flow was measured at site 16 at 0.24 m/day. The fastest flows were measured at sites 2 and 4, at >2.5m/day. Most sites had groundwater flow between 0.5 and 1 m/day. All measured velocities were positive, thus none of the sites experienced loss of lakewater to groundwater. These measurements of seepage represent point scale groundwater influx.

## Estimating septic system impacts

We have created a model to estimate septic tank locations across the Lower Peninsula of Michigan (Luscz et al. 2015). To more accurately estimate septic systems at the relatively small scale of Higgins Lake, we used maps of land parcels for the region (courtesy of Roscommon County), making the assumption that each parcel includes one septic system. Using the parcel map and a map of groundwater elevations, we can estimate the number of septic tanks affecting each sampling location. Figure 5 shows the location of each MSU sampling location and the simulated groundwater elevations in the surrounding area (Kendall et. al 2016). Similar in interpretation to topographic maps, the contours (red) show the estimated surface of the groundwater table. Septic tanks within a 100m buffer of the direct upgradient groundwater flowpath (yellow) were summarized over 1000m and 400m along the upgradient flowpath for this analysis.

As another measure of groundwater influence, we have used these flowlines and groundwater table elevations estimated from drinking water well records to estimate the hydraulic gradient for each site. While seepage meters measure site-specific groundwater inflow, the calculated hydraulic gradient represents the bulk groundwater influx to the broader area around each sampling location. Using these two measures together provides a more comprehensive view of groundwater inputs to Higgins Lake.
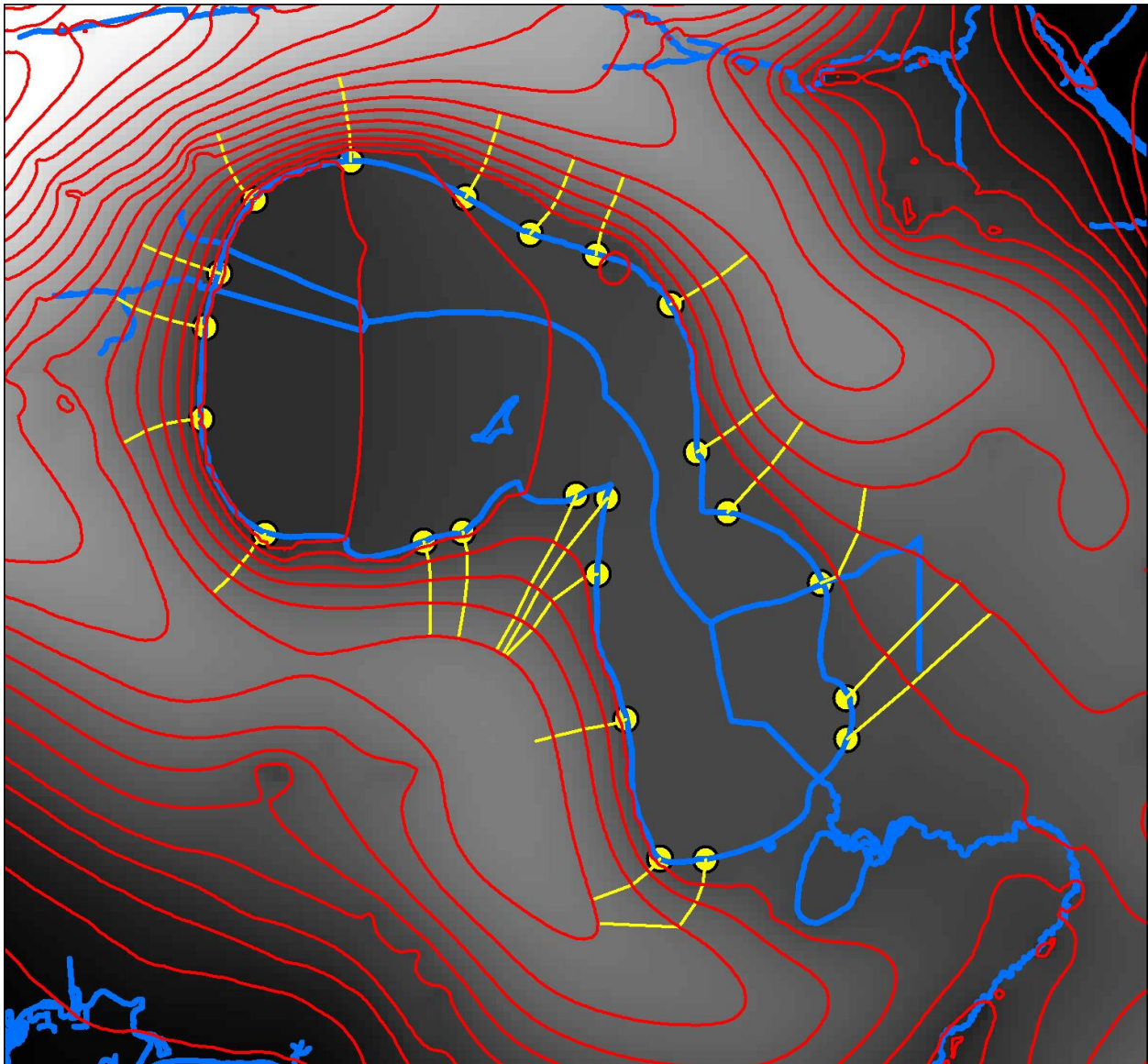
**Figure 5.** *Map of model-simulated groundwater table elevations (shading) along with contoured water table elevations (red lines), sampling locations (yellow dots) and upgradient flowpaths (yellow lines).*

# Water Chemistry Results

This section presents five key water chemistry variables: 1) phosphorus, 2) nitrogen, 3) specific conductivity, 4) chloride, and 5) boron. While the first two variables are of key interest because they drive biotic activity in the lake, interpreting their results is complicated by the complex nature of their cycling within the lake. Specific conductivity is a measure of total solutes in water, and can be measured rapidly in the field. Chloride is a pollutant of increasing concern across lakes in the upper midwest associated with sources including road salt, water softeners, and natural brines. Boron is an indicator of human septic influence, which transports easily through groundwater,

and is only minimally affected by biological activity. Data for all other measured constituents are not explicitly analyzed in this report, and made available in the Appendix.

## Background - Trophic State Index

Trophic State Index is a classification system based on phosphorus, water transparency as measured by Secchi disk depth, and algal biomass measured by chlorophyll-a. It is used to compare biological productivity among multiple lakes or within an individual lake over time. The three main trophic status categories are Oligotrophic (low nutrient), Mesotrophic (moderate nutrient), and Eutrophic (high nutrient). We have used trophic state based on phosphorus measurements to compare among groundwater and surface water results. See Table 2 for phosphorus ranges for each trophic state classification.

**Table 2.** *Trophic state indicators chlorophyll (Chl), Secchi depth (SD), and total phosphorus (TP). Modified from the North American Lake Management Society (www.secchidipin.org/index.php/monitoring-methods/trophic-state-equations/)*

| Chl (µg/L) | SD (m) | TP (µg/L) | Attributes |
|---|---|---|---|
| < 0.95 | > 8 | < 6 | **Oligotrophy:** Clear water, oxygen throughout the year in the hypolimnion. |
| 0.95 – 2.6 | 8 – 4 | 6 – 12 | Hypolimnia of shallower lakes may become anoxic. |
| 2.6 – 7.3 | 4 – 2 | 12 – 24 | **Mesotrophy:** Water moderately clear; increasing probability of hypolimnetic anoxia during summer. |
| 7.3 – 20 | 2 – 1 | 24 – 48 | **Eutrophy:** Anoxic hypolimnia, macrophyte problems possible. |
| 20 – 56 | 0.5 – 1 | 48 – 96 | Blue-green algae dominate, algal scums and macrophyte problems. |
| 56 – 155 | 0.25 – 0.5 | 96 – 192 | **Hypereutrophy:** (light limited productivity). Dense algae and macrophytes. |
| > 155 | < 0.25 | 192 – 384 | Algal scums, few macrophytes |

# Phosphorus (TP and TDP)

In this section we present results for both Total Phosphorus (TP) and Total Dissolved Phosphorus (TDP). The difference between these measures is that the TDP samples were first filtered (0.45 um filter) prior to analysis, while TP samples are whole-water. Since phosphorus strongly sorbs (attaches) to particles such as sediment, and can be a significant component of larger particles of biological origin, TDP concentrations are in general lower than TP. The USGS only analyzed for TP. We also included TDP analyses because they can provide a better indicator of biological availability.

## Summer 2014

Water quality characteristics from surface water and groundwater samples collected from our study sites varied substantially. Average TDP concentrations in groundwater varied widely, from 0.004 to 0.071 ppm, in comparison to surface water concentrations, which ranged from 0.004 to 0.028 (Table 3). The maximum TDP concentration in groundwater was also higher than the surface water maximum.

Groundwater mean TDP concentrations were significantly greater than surface water mean phosphorus concentrations ($p < 0.05$). Specifically, four sites had mean groundwater TDP concentrations >20 ppb higher than surface water concentrations. Three of these sites (8, 10, and 15) all had eutrophic groundwater and oligotrophic surface water, whereas site 5 had eutrophic groundwater and surface water.

Only one site had mean surface water TDP concentrations higher than mean groundwater concentrations (site 2). Although this difference was small (12 ppb), it spans the range of a trophic class. Groundwater mean phosphorus concentrations at site 2 are categorized as mesotrophic, whereas surface water mean phosphorus concentrations are categorized as eutrophic.

*Table 3. Summary statistics for total dissolved phosphorus per site from groundwater and surface water samples reported in mg/L (equivalent to parts per million, ppm). Convert values to ug/L (equivalent to parts per billion, ppb) by multiplying by 1000. n=number of samples analyzed from site. Max=maximum concentration observed at site. Min=minimum concentration observed at site.*

| | Groundwater TDP (mg/L) | | | | Surface Water TDP (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|
| **Site** | **n** | **Max** | **Mean** | **Min** | **n** | **Max** | **Mean** | **Min** |
| 2 | 12 | 0.025 | 0.017 | 0.010 | 12 | 0.076 | 0.028 | 0.006 |
| 3 | 14 | 0.053 | 0.010 | 0.003 | 14 | 0.024 | 0.007 | 0.002 |
| 4 | 11 | 0.009 | 0.004 | 0.002 | 11 | 0.061 | 0.011 | 0.002 |
| 5 | 8 | 0.056 | 0.049 | 0.041 | 8 | 0.059 | 0.025 | 0.014 |
| 6 | 9 | 0.009 | 0.004 | <0.001 | 10 | 0.016 | 0.005 | 0.001 |
| 7 | 8 | 0.014 | 0.012 | 0.011 | 8 | 0.007 | 0.004 | 0.002 |
| 8 | 8 | 0.374 | 0.071 | 0.002 | 8 | 0.029 | 0.011 | 0.002 |

| 9 | 10 | 0.041 | 0.017 | 0.005 | 10 | 0.018 | 0.009 | 0.004 |
|---|----|-------|-------|-------|----|-------|-------|-------|
| 10 | 8 | 0.057 | 0.025 | 0.015 | 8 | 0.010 | 0.004 | 0.001 |
| 13 | 12 | 0.083 | 0.011 | <0.001 | 12 | 0.010 | 0.004 | <0.001 |
| 16 | 8 | 0.077 | 0.029 | 0.010 | 8 | 0.012 | 0.006 | 0.003 |
| 18 | 8 | 0.037 | 0.008 | 0.002 | 8 | 0.010 | 0.005 | 0.003 |
| 19 | 8 | 0.015 | 0.008 | 0.005 | 8 | 0.026 | 0.009 | 0.003 |
| 22 | 10 | 0.014 | 0.005 | 0.002 | 10 | 0.015 | 0.007 | 0.002 |
| 23 | 12 | 0.013 | 0.007 | 0.004 | 12 | 0.019 | 0.005 | 0.001 |

## Temporal Trends

Deep water samples from both basins of Higgins Lake have been low in phosphorus since monitoring of the lake has been recorded, categorizing this lake as Oligotrophic (Figure 6). However, surface water samples from nearshore areas collected by the USGS showed that some sites had elevated concentrations over a similar time frame (Figure 7). Several sites had surface water concentrations in the mesotrophic category (3, 10, 12, 22, 23, 24, and 29). Looking across all of the USGS samples, USGS site 24 was the only site that had eutrophic phosphorus results in surface water. Also of note is the upward trend of site 29 into mesotrophic status.

*Where possible, the results are presented as paired graphics showing USGS data across all available years and comparable data collected by this study (labeled MSU). The figures are intended to show trends over time, and similarities or differences across a range of sites. There are many overlapping (and non-uniquely identified) lines that are not intended for site-by-site comparison, except where individual sites have been labeled.*
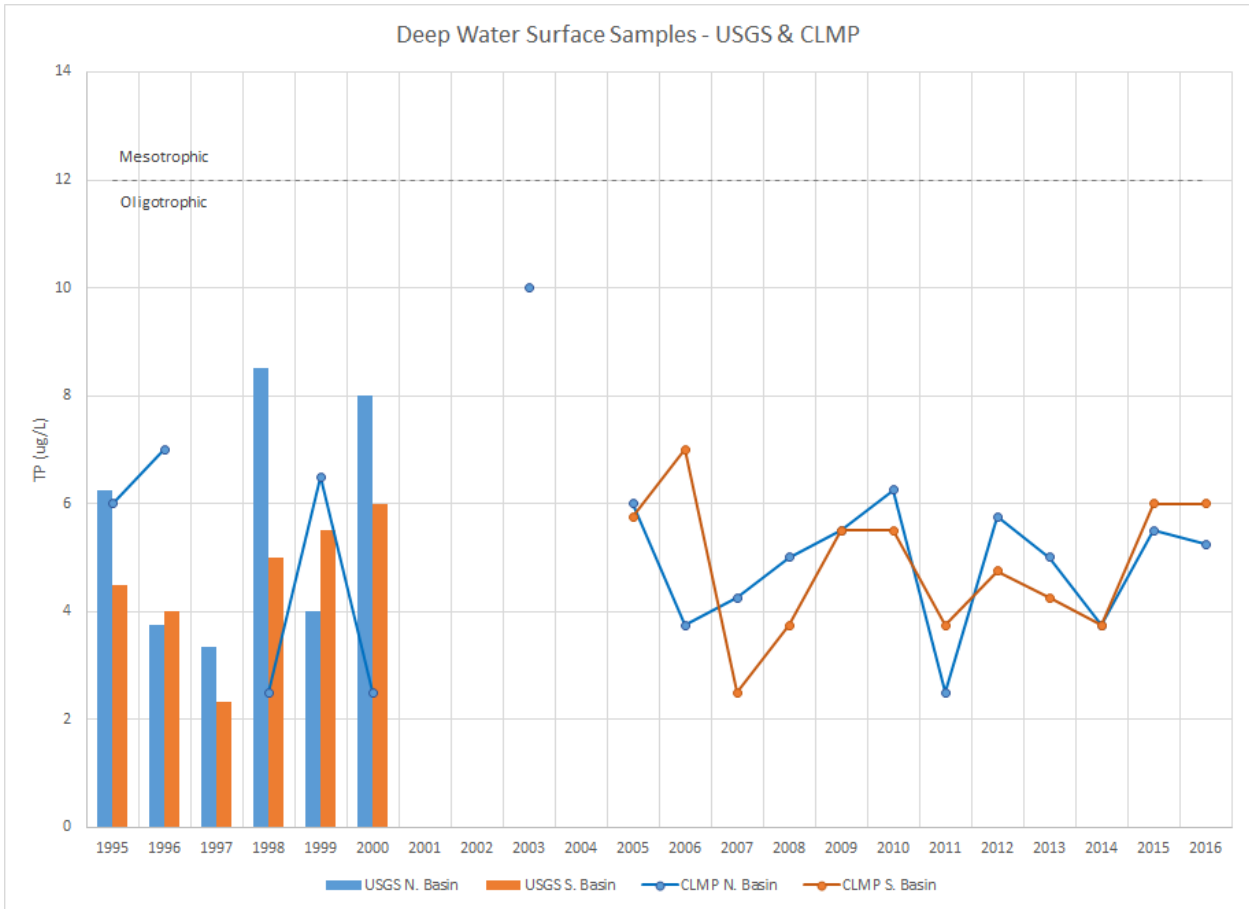
**Figure 6.** *Deep-water surface water phosphorus concentrations collected over time by USGS and Citizens Lake Monitoring Program (CLMP).*
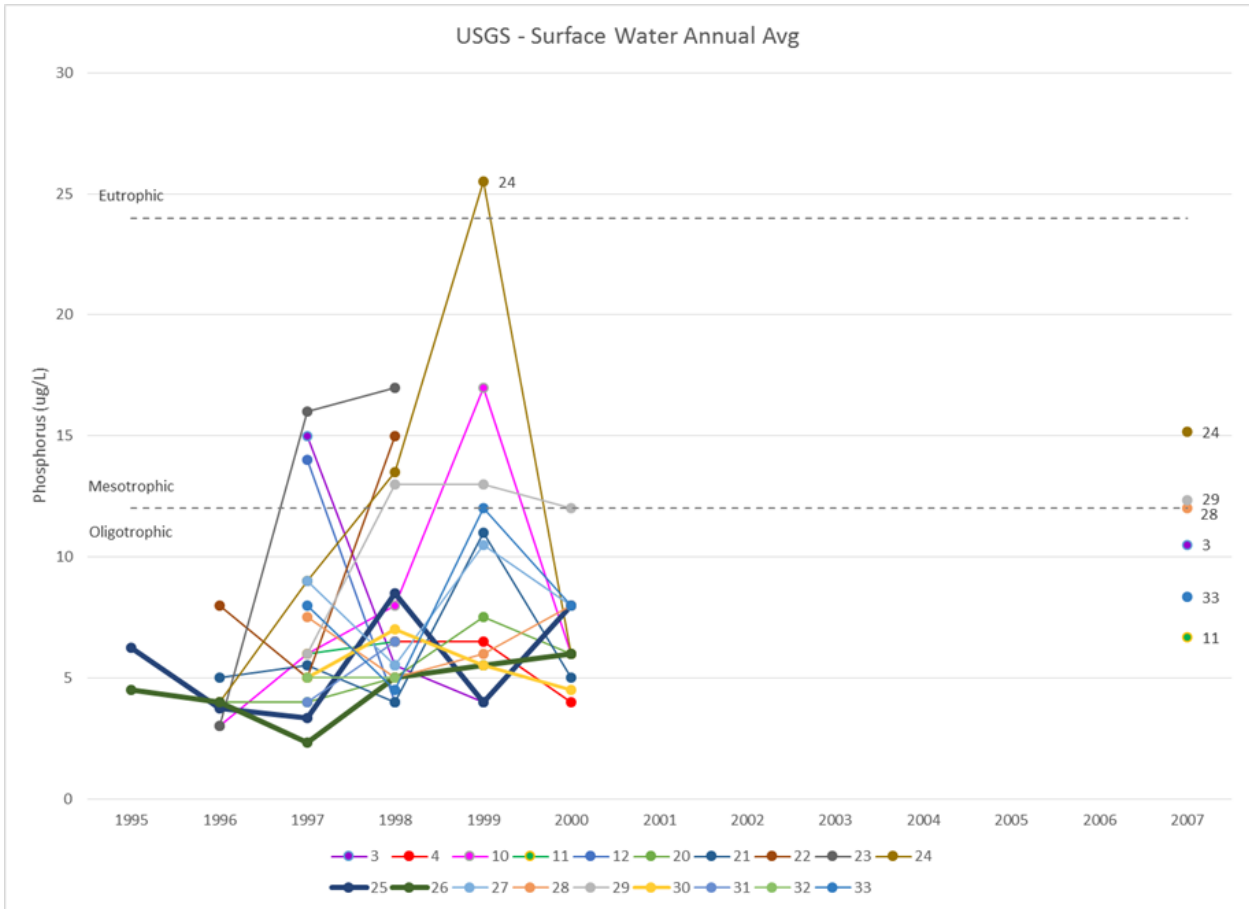
***Figure 7.*** *Annual average phosphorus concentrations collected from USGS nearshore surface water sites over time. Color coded sites are shown at the bottom. Trophic categories are shown as horizontal dashed lines. Note time gap where select sites were revisited in 2007.*

MSU samples show similar trends, with low surface water phosphorus concentrations (below 10 ug/L) for most samples, but also with a few high samples (Figure 8A and 8B). Site 5 has phosphorus concentrations in the mesotrophic range from each of the four sampling trips, and sites 2 and 3 had single eutrophic samples. There were no substantial differences between the four sampling trips. Notably, our sampling did not show elevated surface water phosphorus concentrations after the July 4th holiday.
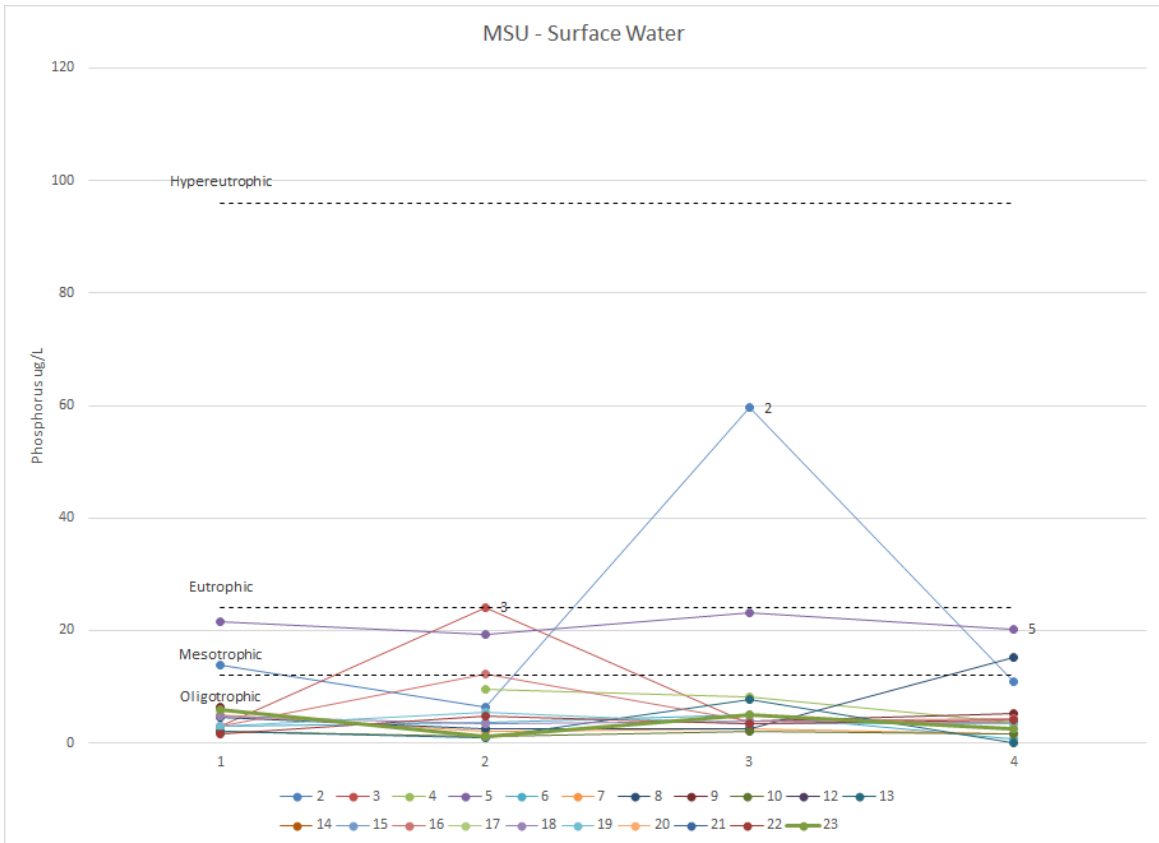
**Figure 8A.** *Filtered near-shore surface water total dissolved phosphorus (TDP) concentrations collected over summer 2014 by MSU. Trip number is indicated along the x-axis (refer to Table 1 for specific date ranges associated with each sampling trip). Color coded sites are shown at the bottom. Trophic categories are shown as horizontal dashed lines.*

**Figure 8B.** *Unfiltered near-shore surface water total phosphorus (TP) concentrations collected over summer 2014 by MSU. Trip number is indicated along the x-axis (refer to Table 1 for specific date ranges associated with each sampling trip). Color coded sites are shown at the bottom. Trophic categories are shown as horizontal dashed lines.*
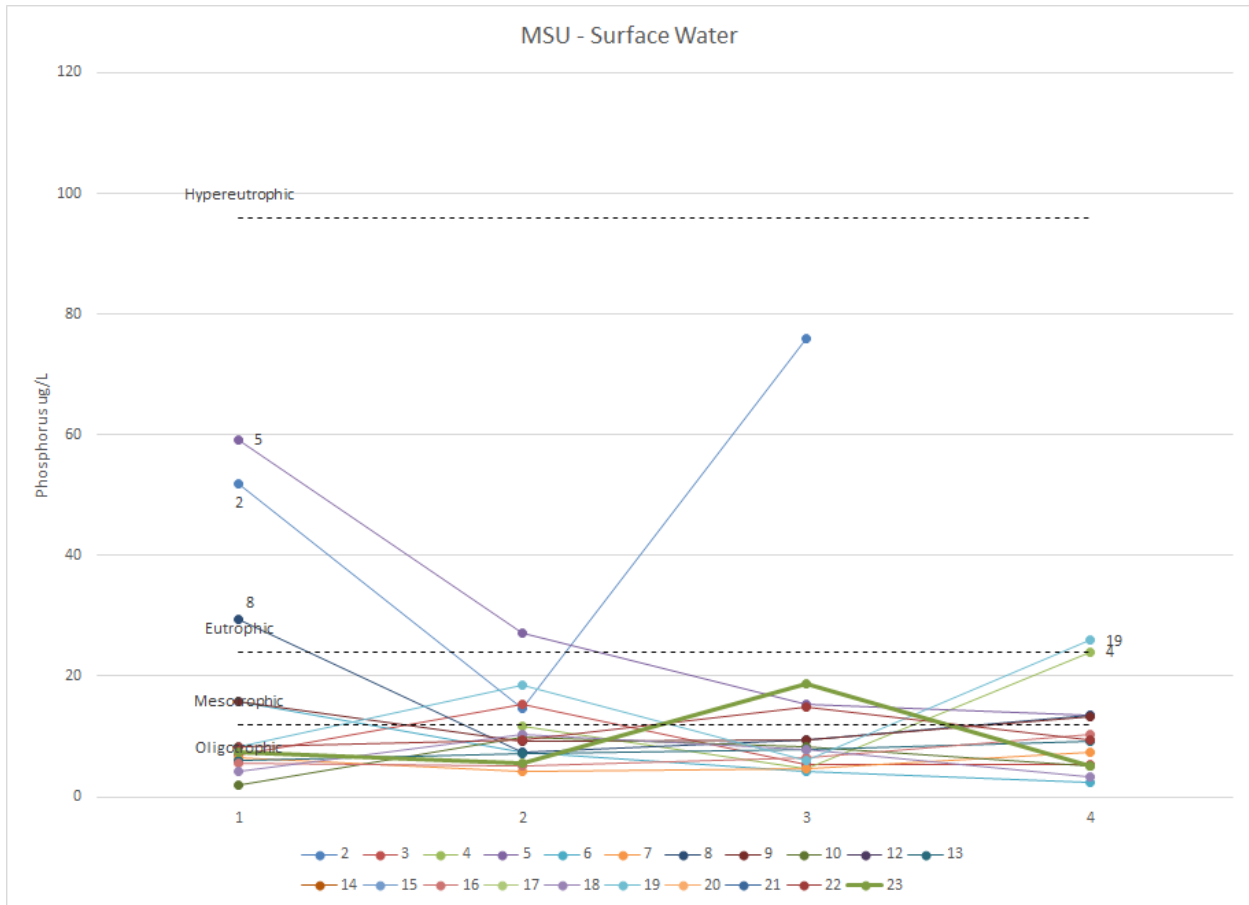
The USGS collected multiple samples from each site per year, which are shown as annual averages in Figures 6 and 7. The full dataset can be used to determine the frequency of samples from a site that had elevated phosphorus concentrations, as shown below in Figure 9. Most USGS sites had oligotrophic to mesotrophic concentrations but site 24 had two samples over the course of their sampling program that indicate eutrophic status.
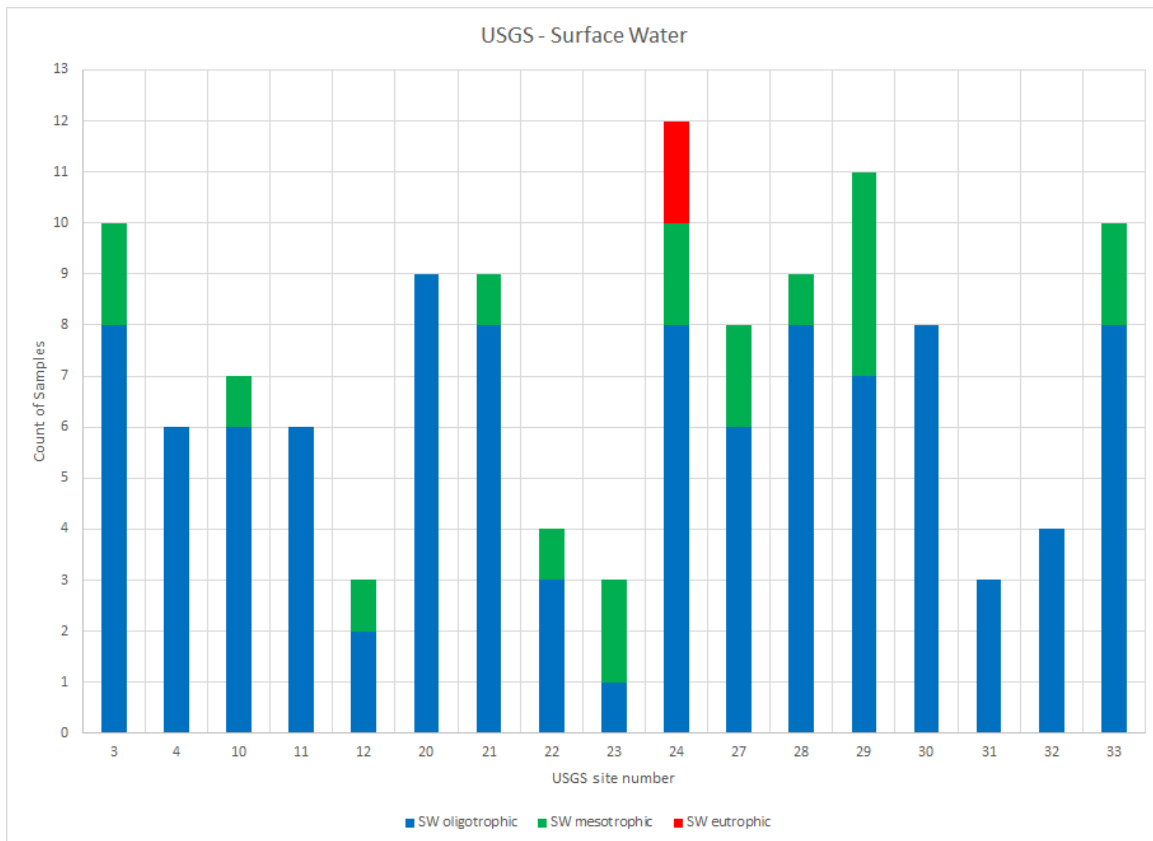
*Figure 9. Number of surface water samples collected at each site by USGS, indicating the trophic state of each sample, determined by phosphorus concentration.*

On the other hand, USGS groundwater samples were predominantly classified as eu- and hypereutrophic (Figure 10). In this analysis, all sites but three (10, 12, and 22) resulted in one or more eutrophic samples. Figure 11 shows the USGS annual average of phosphorus results in the groundwater. These two analyses can be used together to find sites that are experiencing consistently high phosphorus concentrations. There are several sites that have very high annual average phosphorus concentrations but some of those sites experience high concentrations more often than others. For example, USGS site 31 (on the northeast side of Treasure Island) had a very high average concentration in 1998 and is eutrophic the prior year; however, this site was only sampled in those two years. Therefore, additional samples would need to be collected to characterize this site as eutrophic. On the other hand, USGS site 24 is hypereutrophic in 2007 from one sample but has a history of eutrophic and mesotrophic samples.

MSU samples show some high groundwater phosphorus values, similar to what was found in the USGS study, but many more low values than during the USGS study (Figure 12A and 12B). There was only a single sample (site 8) that resulted in a hypereutrophic phosphorus value. Sites 2 and 10 had mesotrophic phosphorus concentrations during the summer sampling months but higher eutrophic concentrations

during the October sampling trip. Site 3 had oligotrophic phosphorus concentrations except during the sampling trip following the July 4th holiday (the 2nd trip). Other sites show mostly oligotrophic phosphorus concentrations.

Due to a freezer failure, sample bottles from the 1st and 2nd trip thawed for some period (likely in the range of 7 days) prior to being re-frozen. This caused some concern for sample preservation, as the literature has shown that phosphorus can attach itself to the polyethylene bottles used for sample collection. However, no significant differences were observed between concentrations in the 1st or 2nd trips, indicating that this was likely not a significant issue.
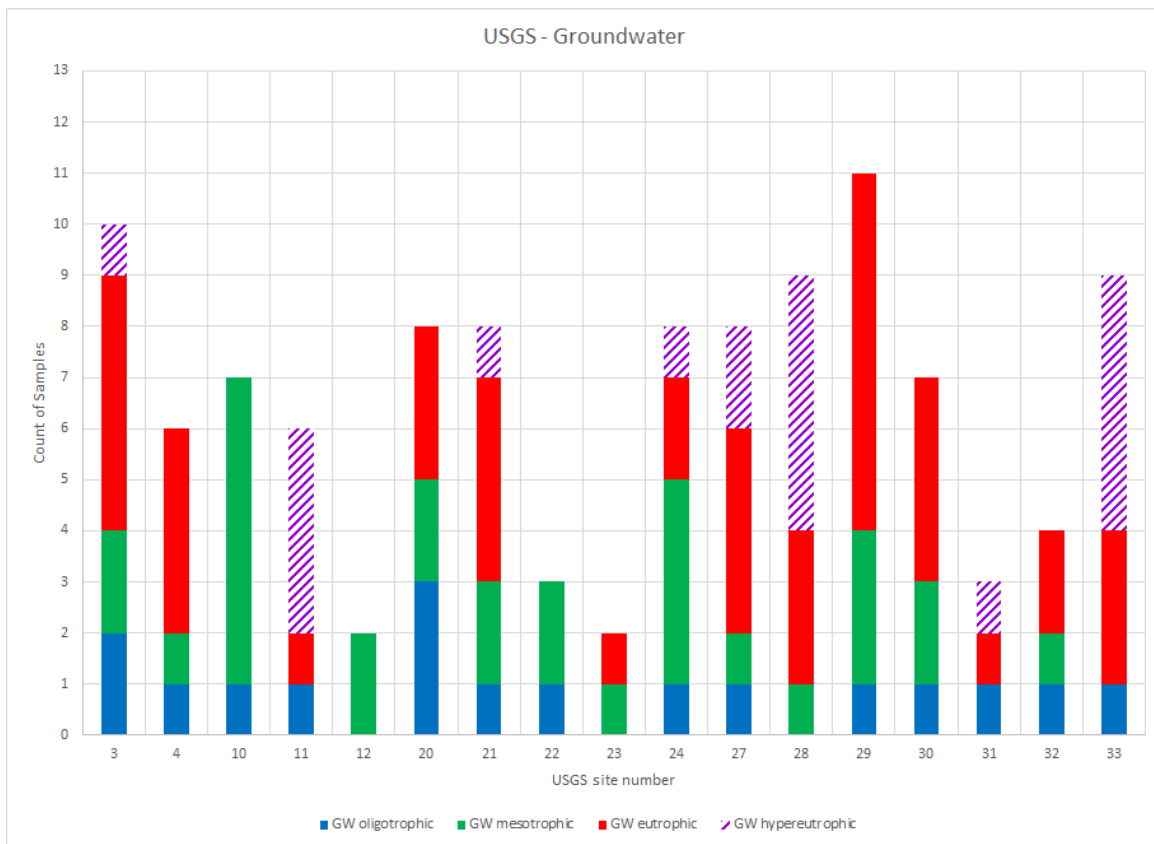


**Figure 10.** *Number of groundwater samples collected at each site by USGS, indicating the trophic state of each sample, determined by phosphorus concentration.*
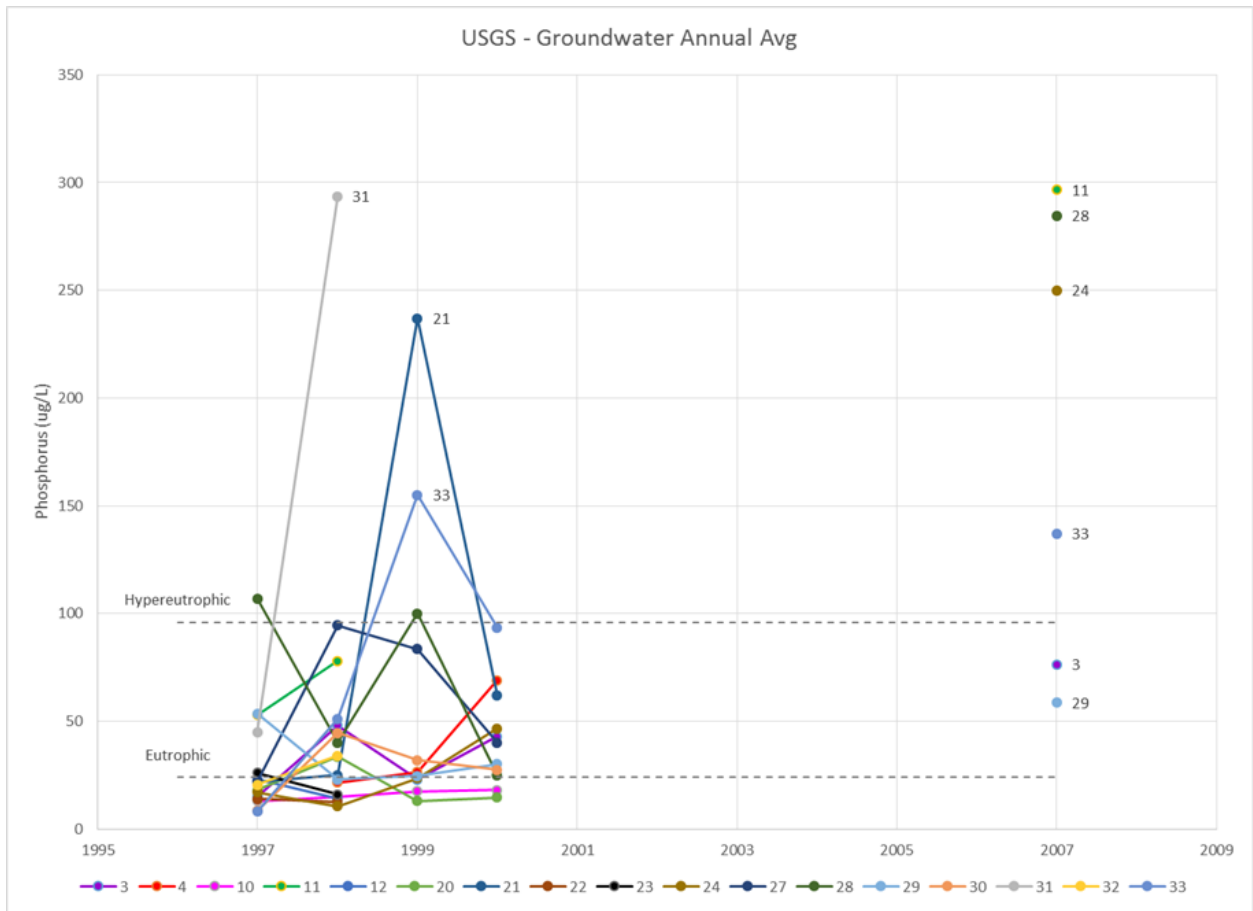
***Figure 11.*** *Annual average phosphorus concentrations collected from USGS nearshore groundwater sites over time. Color coded sites are shown at the bottom. Trophic categories are shown as horizontal dashed lines.*

**Figure 12A.** Filtered near-shore groundwater total dissolved phosphorus (TDP) concentrations collected over summer 2014 by MSU. Trip number is indicated along the x-axis (refer to Table 1 for specific date ranges associated with each sampling trip). Color coded sites are shown at the bottom. Trophic categories are shown as horizontal dashed lines.

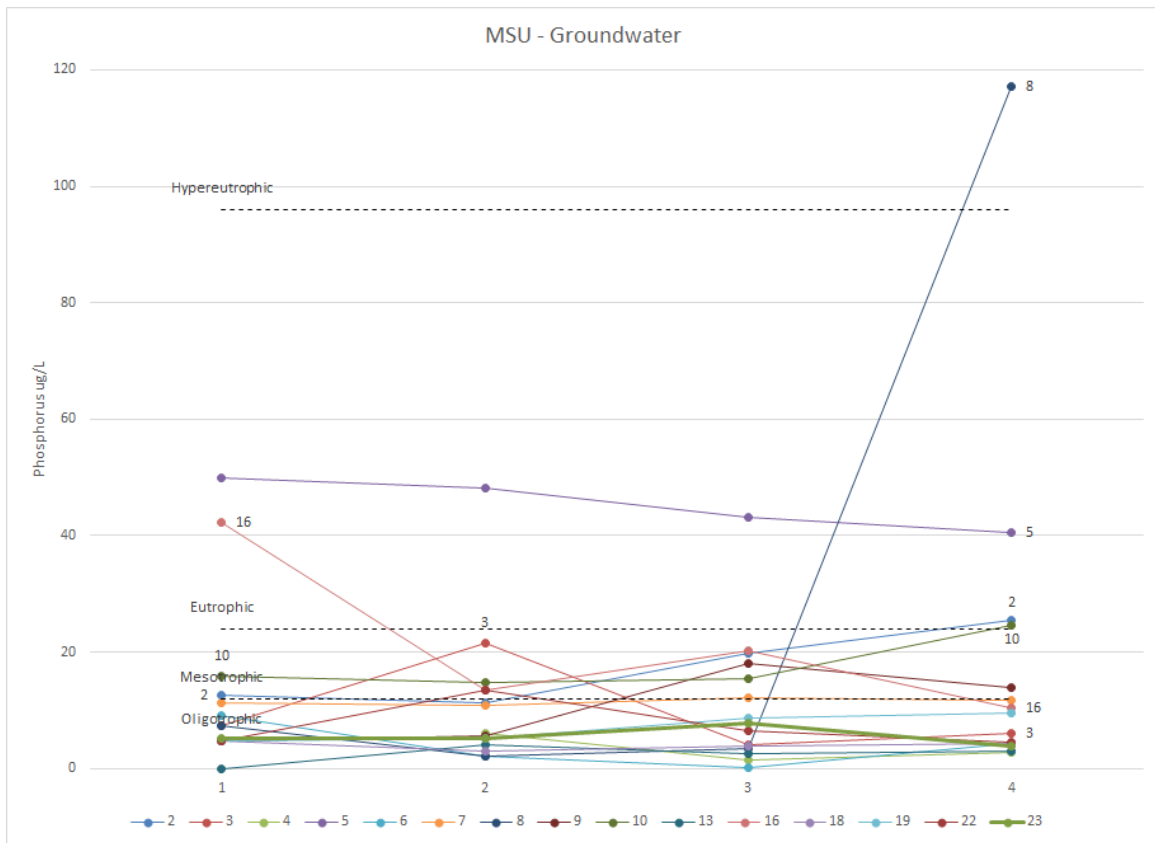**Figure 12B.** *Unfiltered near-shore groundwater total phosphorus (TP) concentrations collected over summer 2014 by MSUTrip number is indicated along the x-axis (refer to Table 1 for specific date ranges associated with each sampling trip). Color coded sites are shown at the bottom. Trophic categories are shown as horizontal dashed lines.*
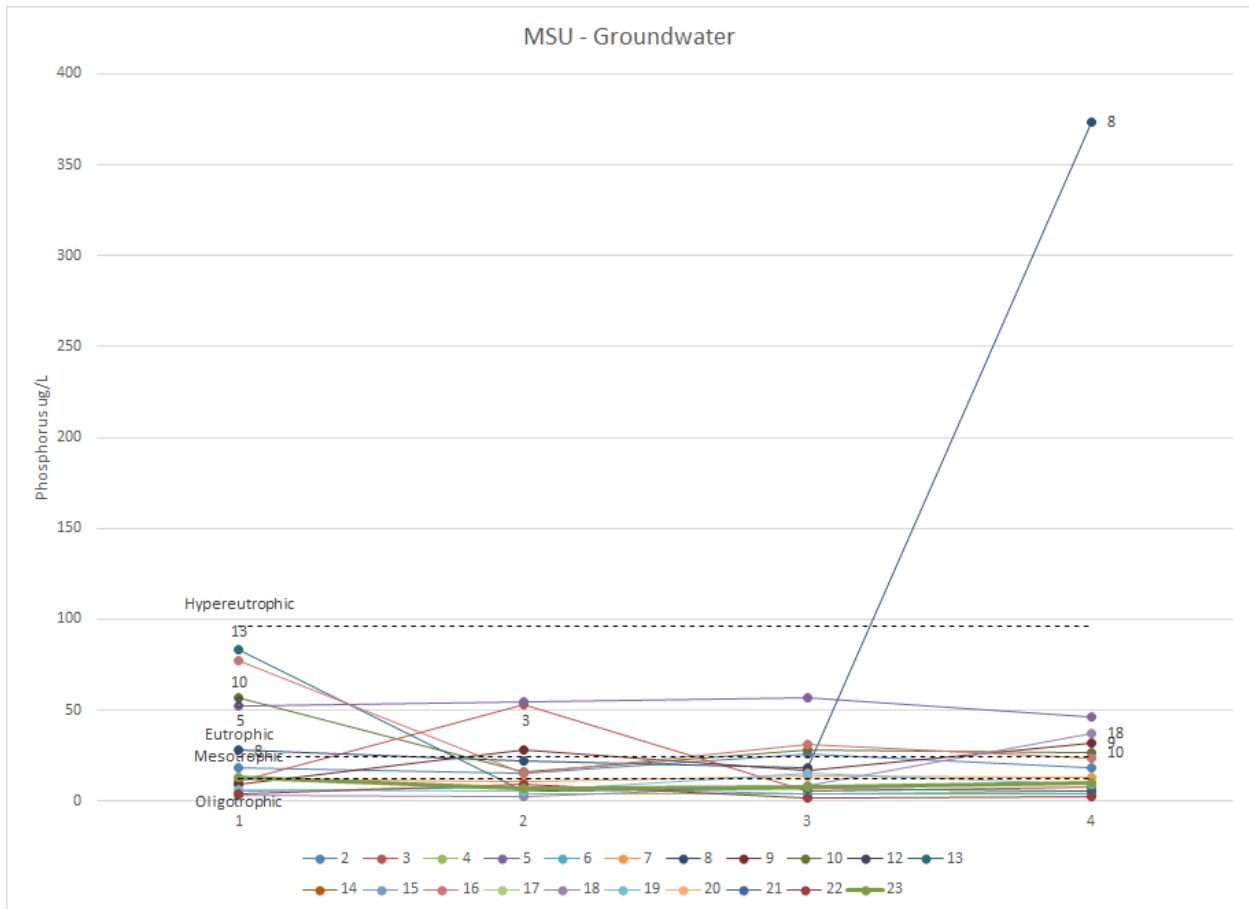
Interesting differences emerge between the results of this study and that conducted by the USGS approximately 15 years prior (summarized in Table 4). Overall, we observed a significant increase in TP concentrations in surface water, 12.9 ug/L versus 7.5 ug/L in the USGS study. This indicates that bulk TP concentrations in near shore surface waters have likely increased since that study. The exact amount of that increase is unclear, as this study included a single year of sampling, and the USGS study included annual averages ranging from 4.1 to 9.7 ug/L. Nevertheless, 2014 average nearshore surface water concentrations crossed the threshold into mesotrophic category (Table 2).

In contrast, our groundwater TP concentrations were substantially lower than those reported by the USGS. Here, a methodological difference between the two studies may inhibit direct comparison. The USGS sampling involved driving a temporary sampling piezometer into the lake sediments for each site and sampling date. Here, we installed semi-permanent piezometers, allowing them to equilibrate for several days prior to sampling and used low-flow sampling procedures to minimize

sediment intake. Because phosphorus attaches so readily to sediment (leading to approximately double the phosphorus concentrations between TP and TDP in both groundwater and surface water), this factor may lead to higher TP concentrations in the USGS study, compared to those we observed.

*Table 4. Summary of overall nearshore surface water (SW) and groundwater (GW) phosphorus average concentrations between USGS and MSU studies*

| Study | Years | Location | Species | Concentration (ug/L) |
|-------|-------|----------|---------|----------------------|
| USGS | 1996-2000 | SW | TP | 7.1 |
| USGS | 1996-2000 | GW | TP | 47.4 |
| MSU | 2014 | SW | TP | 12.9 |
| MSU | 2014 | GW | TP | 22.9 |
| MSU | 2014 | SW | TDP | 6.5 |
| MSU | 2014 | GW | TDP | 12.5 |

Looking more closely to compare USGS and MSU phosphorus concentrations (Figure 13 and Table 5), USGS site 24 and 29 had multiple samples with meso- and eutrophic concentrations of phosphorus (and in groundwater, hyper-eutrophic). USGS site 23 had lower phosphorus concentrations during the 2 years it was sampled (1997 and 1998). MSU samples from nearby sites 22 and 23 did not show any signs of elevated phosphorus levels in the surface water, with all samples below 10 ug/L. This could be due to different sampling depths between the two studies, slightly different sampling locations relative to the shoreline, a change in processes in the mixing zone between lake and groundwater, or a change in the groundwater phosphorus load over time. Furthermore, concentrations in both the nearshore surface water and groundwater seem to have also shifted from an upward trend in phosphorus concentrations in the mid- to late- 1990's to a more oligo- to mesotrophic character in summer 2014.

The Camp Curnalia Sewer project, completed in 2009, was designed to redirect household waste from 400+ septic-served residences in this area to a sewage treatment facility. Our results show that phosphorus concentrations in the subsurface of this area have been greatly reduced since the Camp Curnalia Sewer project came online. Critically, groundwater TP values decreased by a factor of 4-5x in 2014 relative to late 1990s data--greatly exceeding the uncertainties due to different sampling methods in the two studies. Importantly, the surface water TP concentrations also declined by approximately 2-3 ug/L from the USGS to the MSU study, whereas lake-wide concentrations increased over the same period (Table 4).

*Table 5. Comparison of average TP values from the USGS and MSU studies in the Camp Curnalia area along with periods averaged for each.*

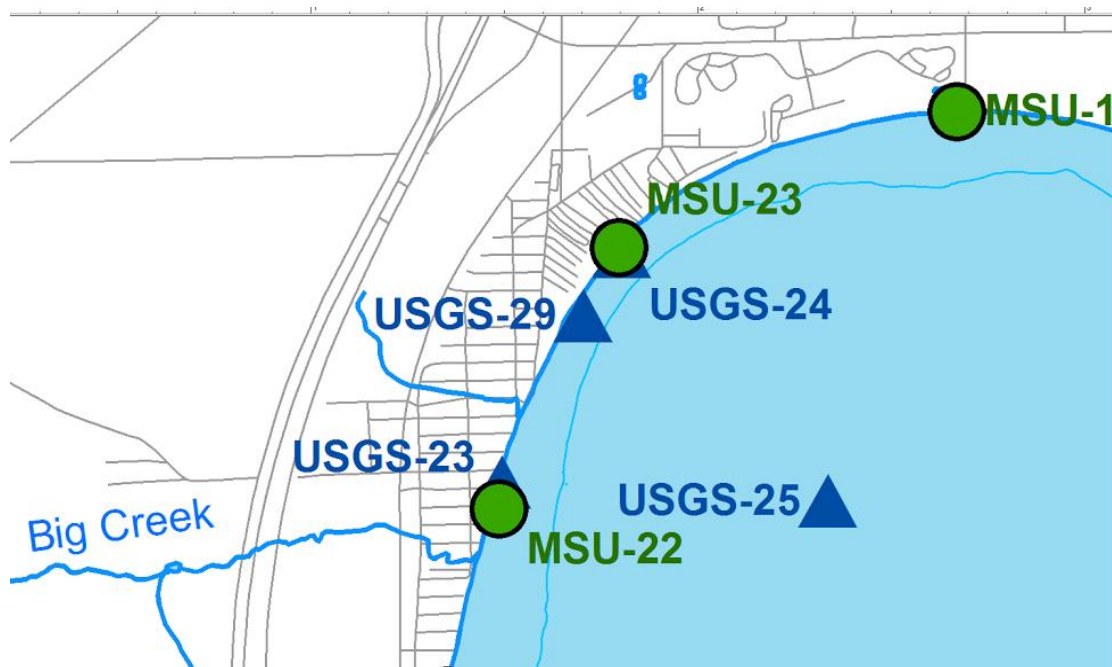| Site Number | Period Averaged | Surface water TP (ug/L) | Groundwater TP (ug/L) |
|---|---|---|---|
| USGS-23 | 1997-1998 | 12.0 | 21.0 |
| USGS-24 | 1996-2000, 2007 | 11.6, 15.2 | 24.3, 250 |
| USGS-29 | 1997-2000, 2007 | 11.0, 12.3 | 32.8, 58.7 |
| MSU-22 | 2014 | 10.3 | 4.2 |
| MSU-23 | 2014 | 8.5 | 8.7 |



*Figure 13. Close-up map of north-west corner of Higgins Lake, highlighting MSU sites 23 and 22 and USGS sites 23, 24, and 29. Many cottages in this area have been converted from onsite septic systems to sewage treatment through the Camp Curnalia Sewer project.*

# Nitrogen (NO$_3$+NO$_2$)

## Summer 2014

Nitrogen, measured as N in nitrate-nitrite (NO$_3$+NO$_2$), was well below the EPA drinking water limit (10 ppm) during all 2014 sampling events (Table 6). All but two sites had very low average concentrations of NO$_3$+NO$_2$, below 1 ppm, in both surface and groundwater samples. Sites 12 and 15 had higher measured average concentrations, at 1.9 and 7.5 ppm. Both of these sites also had a narrow range of concentrations, varying between 1.1 and 2.4 at site 12 and 6.9 and 9.3 at site 15. This result means that the source of NO$_3$+NO$_2$ is consistent across our sampling events at these sites.

At most sites, groundwater was enriched in NO$_3$+NO$_2$ when compared with surface water. However, the concentrations at the majority of the sites were still low enough not to cause concern. For example, although site 2 had 40x higher NO$_3$+NO$_2$ concentrations in groundwater than surface water, these concentrations were all still below 1 ppm. On the other hand, site 15 had groundwater concentrations 750x and 2 orders of magnitude above the surface water. Surface water at both sites 2 and 15 were quite low in NO$_3$+NO$_2$ concentrations, but groundwater NO$_3$+NO$_2$ concentrations at site 15 were much higher than all other sites. Continued monitoring of groundwater NO$_3$+NO$_2$ at site 15 would be prudent to preserve water quality.

*Table 6.* *Summary statistics for nitrate-nitrite (NO$_3$+NO$_2$) per site from groundwater and surface water samples reported in mg/L (equivalent to ppm). n=number of samples analyzed from site. Max=maximum concentration observed at site. Min=minimum concentration observed at site.*

| | Groundwater NO$_3$+NO$_2$ (mg/L) | | | | Surface Water NO$_3$+NO$_2$ (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|
| Site | n | Max | Mean | Min | n | Max | Mean | Min |
| 2 | 7 | 0.431 | 0.404 | 0.281 | 7 | 0.046 | 0.010 | <0.001 |
| 3 | 10 | 0.279 | 0.270 | 0.263 | 10 | 0.020 | 0.013 | <0.001 |
| 4 | 5 | 0.111 | 0.102 | 0.089 | 5 | 0.082 | 0.036 | 0.001 |
| 5 | 4 | 0.012 | <0.001 | <0.001 | 4 | 0.054 | 0.016 | 0.001 |
| 6 | 4 | 0.087 | 0.078 | 0.063 | 5 | 0.012 | 0.005 | 0.001 |
| 7 | 4 | <0.001 | <0.001 | <0.001 | 4 | 0.006 | 0.002 | <0.001 |
| 8 | 4 | 0.007 | <0.001 | <0.001 | 4 | 0.001 | <0.001 | <0.001 |
| 9 | 7 | 0.002 | <0.001 | <0.001 | 7 | 0.383 | 0.115 | 0.001 |
| 10 | 4 | <0.001 | <0.001 | <0.001 | 4 | 0.010 | 0.008 | 0.004 |
| 12 | 4 | 2.450 | 1.865 | 1.190 | 4 | 0.074 | 0.033 | 0.014 |
| 13 | 7 | 0.218 | 0.182 | 0.147 | 7 | 0.039 | 0.010 | <0.001 |
| 14 | 2 | <0.001 | <0.001 | <0.001 | 3 | 0.010 | 0.007 | <0.001 |
| 15 | 8 | 9.280 | 7.526 | 6.920 | 7 | 0.021 | 0.010 | 0.004 |
| 16 | 3 | 0.012 | <0.001 | <0.001 | 4 | 0.036 | 0.011 | 0.001 |
| 17 | 7 | <0.001 | <0.001 | <0.001 | 7 | 0.025 | 0.009 | 0.001 |

| 18 | 4 | 0.526 | 0.502 | 0.470 | 4 | 0.527 | 0.149 | 0.009 |
|----|---|-------|-------|-------|---|-------|-------|-------|
| 19 | 4 | 0.219 | 0.163 | 0.133 | 4 | 0.035 | 0.012 | 0.002 |
| 20 | 3 | 0.003 | <0.001 | <0.001 | 3 | 0.008 | 0.006 | 0.004 |
| 21 | 5 | <0.001 | <0.001 | <0.001 | 7 | 0.044 | 0.018 | 0.002 |
| 22 | 7 | <0.001 | <0.001 | <0.001 | 7 | 0.216 | 0.054 | 0.012 |
| 23 | 7 | 0.042 | <0.001 | <0.001 | 7 | 0.014 | 0.004 | 0.001 |

## Temporal Trends

Surface water $NO_3+NO_2$ concentrations have been low in Higgins Lake throughout the the late 1990's (USGS data, Figure 14) and into 2014 (MSU data, Figure 15), with all values below 1 mg/L. USGS site 30 had a relatively higher annual average $NO_3+NO_2$ concentration in 1997, but fell to very low levels for the remaining years. Similarly, MSU sites 18, 22, and 9 all had single samples with relatively higher $NO_3+NO_2$ concentrations. However, these peak values were still relatively low in concentration.

Groundwater $NO_3+NO_2$ concentrations were much more variable in the late 1990's (USGS data, Figure 16) than in 2014 (MSU data, Figure 17). Maximum annual average groundwater $NO_3+NO_2$ concentration collected during the USGS study was 6.1 mg/L at site 3 in 1998. Concentrations dropped at this site in subsequent years. USGS site 28 also had higher values in 1997 and 1999 but dropped to near the detection limit for the other sampled years. All other USGS sites had annual average groundwater $NO_3+NO_2$ concentrations below 3 mg/L.

Groundwater $NO_3+NO_2$ concentrations collected during the MSU study showed stability throughout the summer with concentrations below 1 mg/L for most sites (Figure 17). However, two MSU sites had groundwater $NO_3+NO_2$ concentrations above 1mg/L: MSU site 12 concentrations ranged narrowly between 2.5 and 1.2 mg/L; and, MSU site 15 concentrations ranged between 9.3 and 7.0. Evaluating the shifts in concentration between each sampling event in the MSU study for these two sites, there is no apparent temporal pattern in these data. It is likely that these sites are responding to site specific phenomena rather than regional climate or other larger scale drivers.
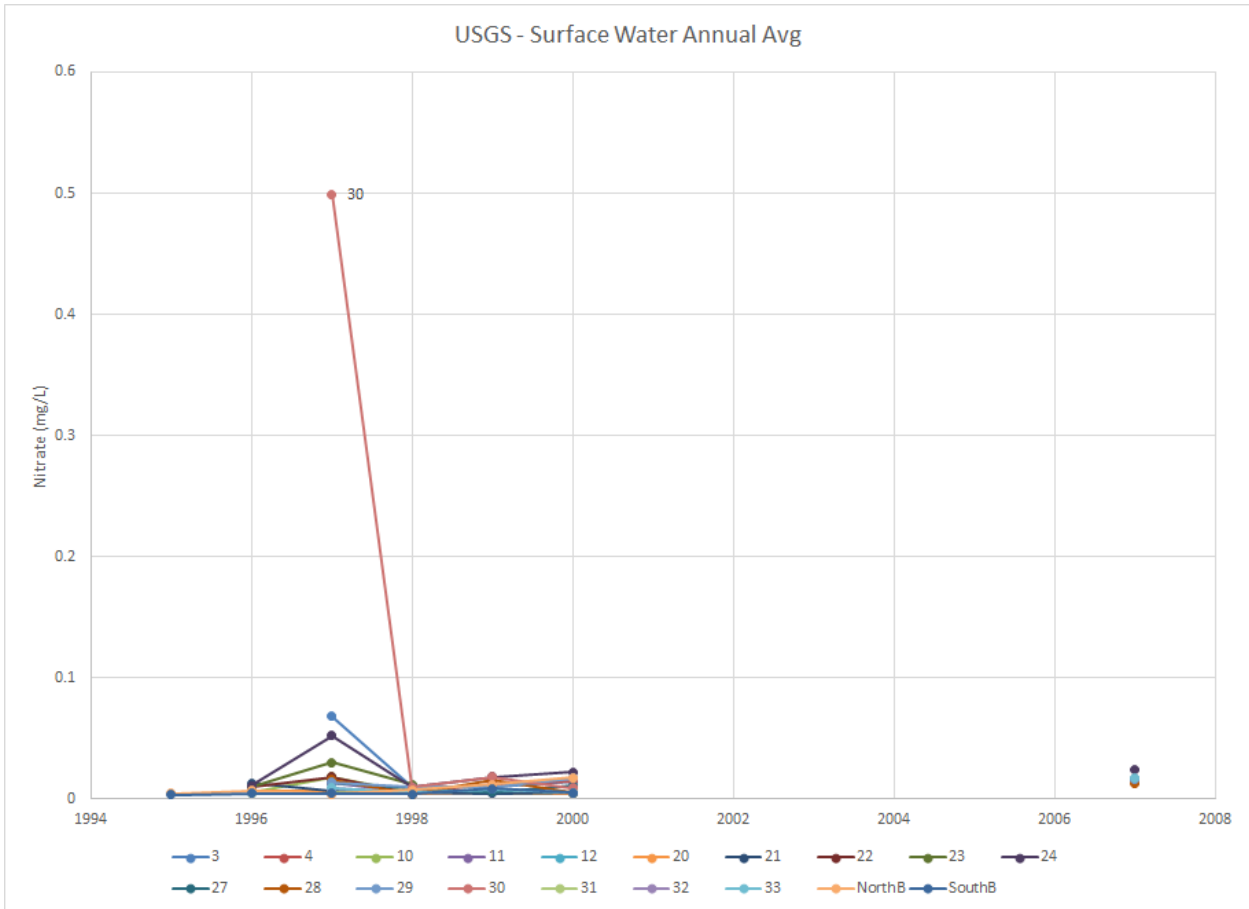
**Figure 14.** *Average annual nitrate-nitrite ($NO_3$+$NO_2$) values collected by USGS from surface water at their shoreline study sites.*
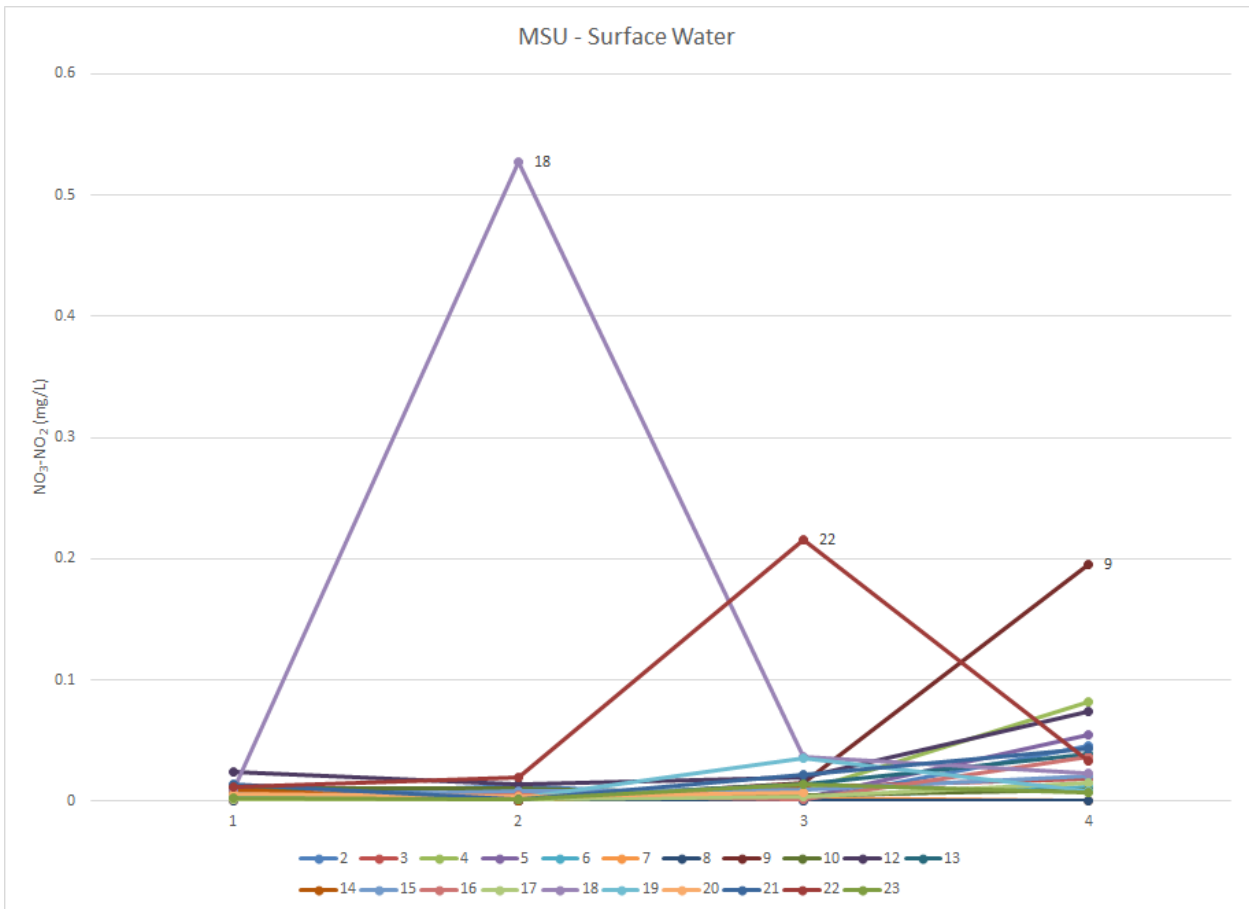
**Figure 15.** *Nitrate-nitrite ($NO_3$+$NO_2$) values collected by MSU from surface water at our shoreline study sites.*
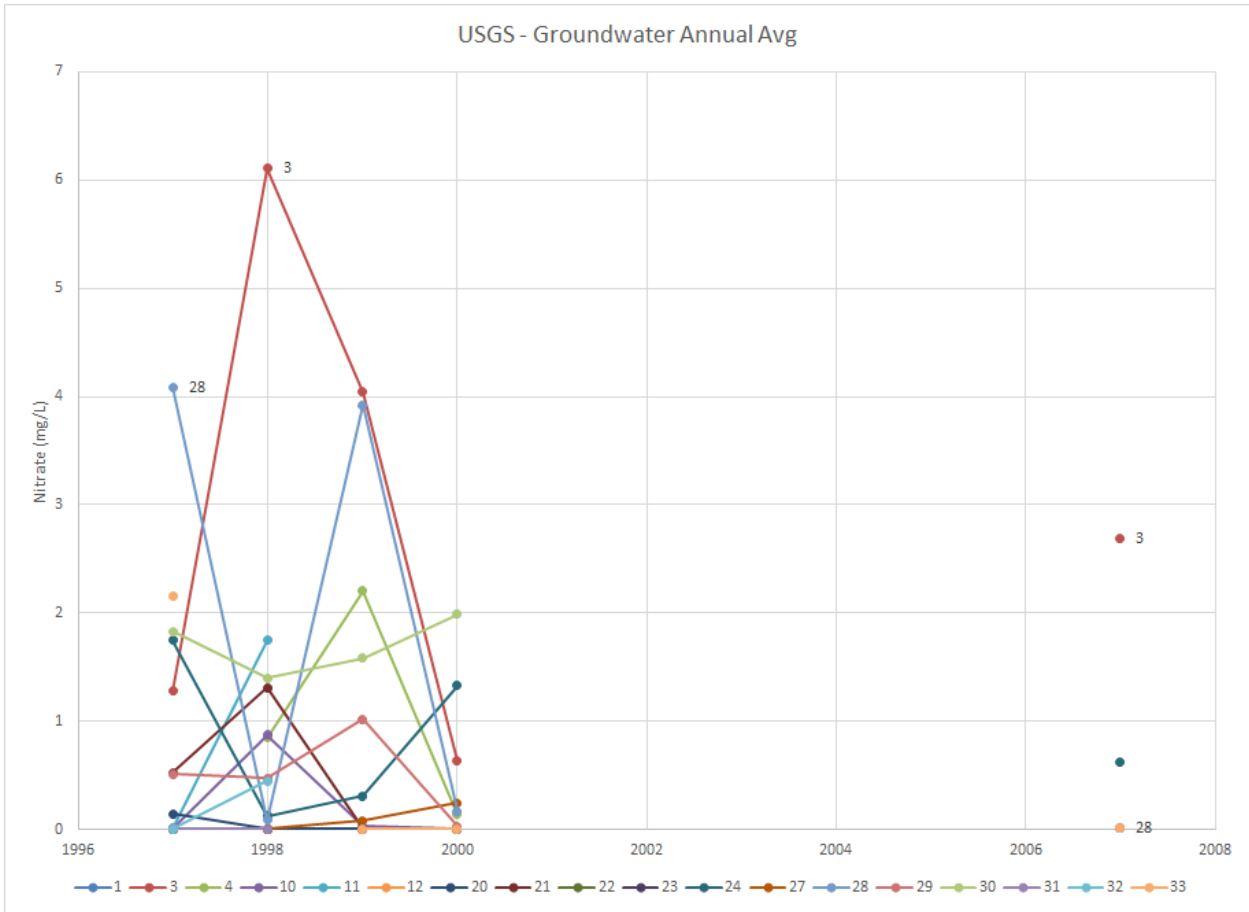
**Figure 16.** *Average annual nitrate-nitrite (NO$_3$+NO$_2$) values collected by USGS from groundwater at their shoreline study sites.*
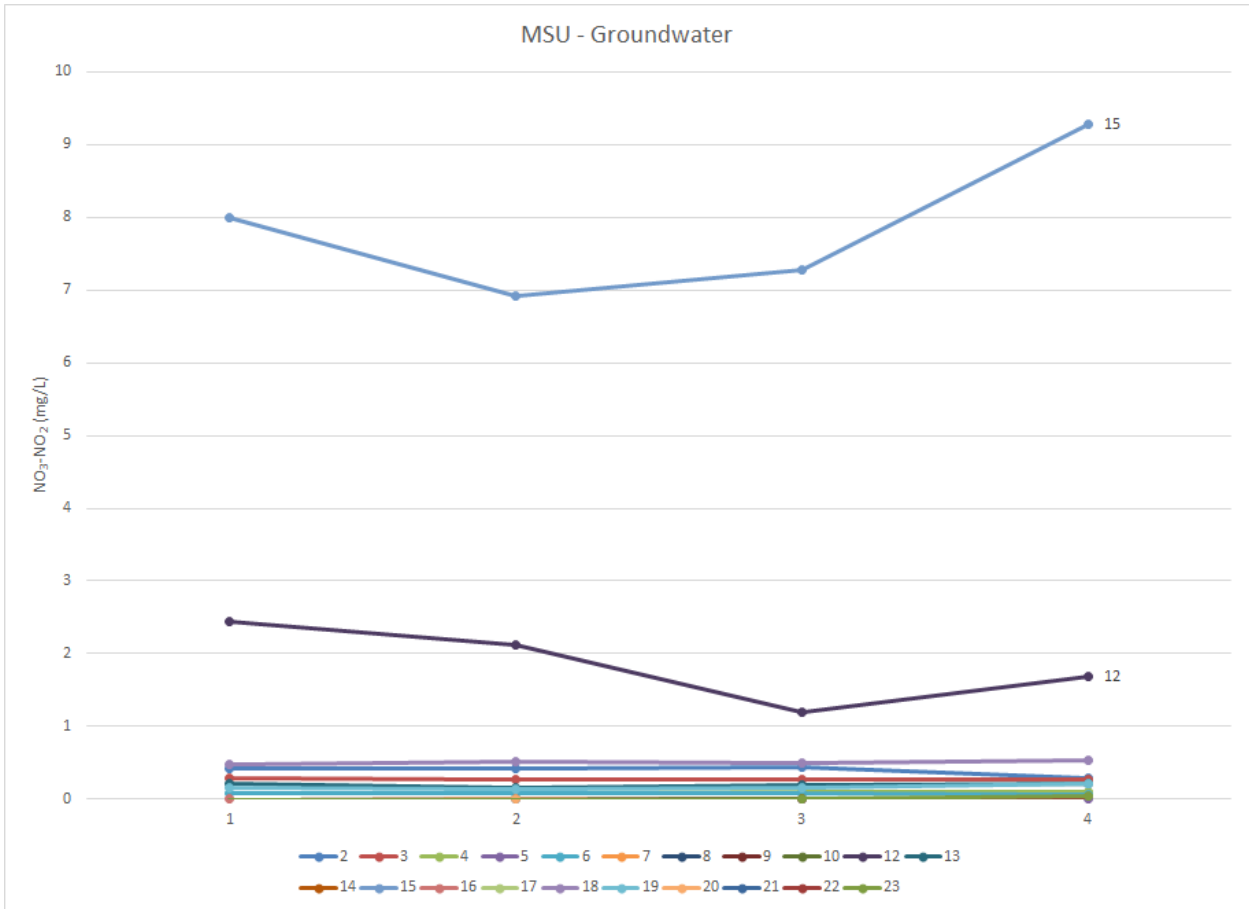
**Figure 17.** *Nitrate-nitrite ($NO_3$+$NO_2$) values collected by MSU from surface water at our shoreline study sites.*

Shown in Table 7 is a comparison of nitrate-nitrite values between the USGS and MSU studies for the Camp Curnalia sites, indicating a substantial decline in groundwater concentrations to below the detection limit for most samples. Surface water concentrations appeared largely unaffected; it should be noted, however, that there are a large variety of N inputs to surface water including nitrogen deposition from the atmosphere that could mask the signal of reduced nitrogen loading from groundwater at these low concentrations. This supports the hypothesis that the Camp Curnalia sewer system has reduced nitrogen loading to the lake.

**Table 7.** *Comparison of average nitrate-nitrite ($NO_3$+$NO_2$) values from the USGS and MSU studies in the Camp Curnalia area along with periods averaged for each.*

| Site Number | Period Averaged | Surface water (mg/L) | Groundwater (mg/L) |
|---|---|---|---|
| USGS-23 | 1997-1998 | 0.017 | 0.0045 |
| USGS-24 | 1996-2000 | 0.024 | 0.877 |

| USGS-29 | 1997-2000 | 0.013 | 0.508 |
|---------|-----------|-------|--------|
| MSU-22 | 2014 | 0.070 | <0.001 |
| MSU-23 | 2014 | 0.006 | <0.001 |

# Specific Conductivity

## Temporal Trends

Specific conductivity measures the electrical conductance of a substance and is related to the concentration of inorganic dissolved solids in water, such as chloride, nitrate, sulfate, and phosphate anions (negatively charged ions) or sodium, magnesium, calcium, iron, and aluminum cations (positively charged ions). Higher conductivity in freshwater systems is indicative of higher concentration of solutes in the water, often times due to pollution. Michigan lakes high in their watersheds typically have conductivity values between 200-300 uS/cm, with values increasing in lakes further down the drainage system (Martin & Soranno 2006).

Surface water specific conductivity values collected over the 5+ years from the 16 USGS shoreline sites show that conductivity varied little around 250 uS/cm (Figure 18, data available for download from http://nwis.waterdata.usgs.gov/). A notable exception includes USGS sites 24 and 29 (Camp Curnalia sites) which are elevated compared with the other sites. Linear regression analysis shows that conductivity values are increasing over this short time period by approximately 3 uS/cm each year.

Surface water specific conductivity at the MSU near-shore sites showed a similar but wider range than the USGS sampling events, varying between 234 and 316 (Figure 19). There was little difference among our sites within a single sampling event. The first and fourth sampling events were similar (average 279 and 277 uS/cm respectively). However, the second and third sampling events were distinct from other events (average 253 and 306 uS/cm, respectively). The overall average of 2014 samples at the MSU sites (278 uS/cm) further indicates a continued increase in surface water specific conductivity.
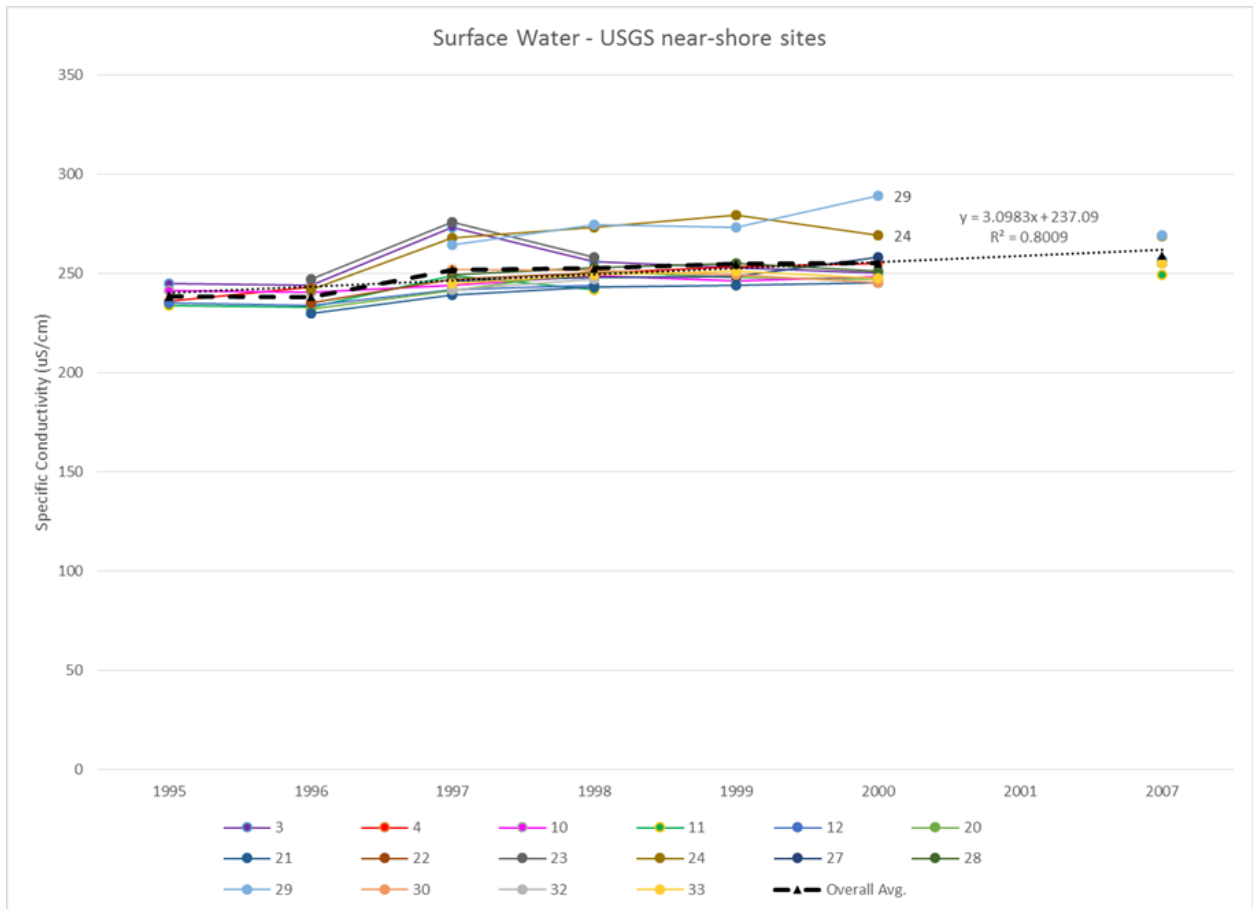
*Figure 18*. Average annual specific conductivity values collected by USGS from surface water at their shoreline study sites. Overall average from all sites per year are shown with black triangles. Linear regression trendline is shown (dotted) with associated equation and fit statistic.
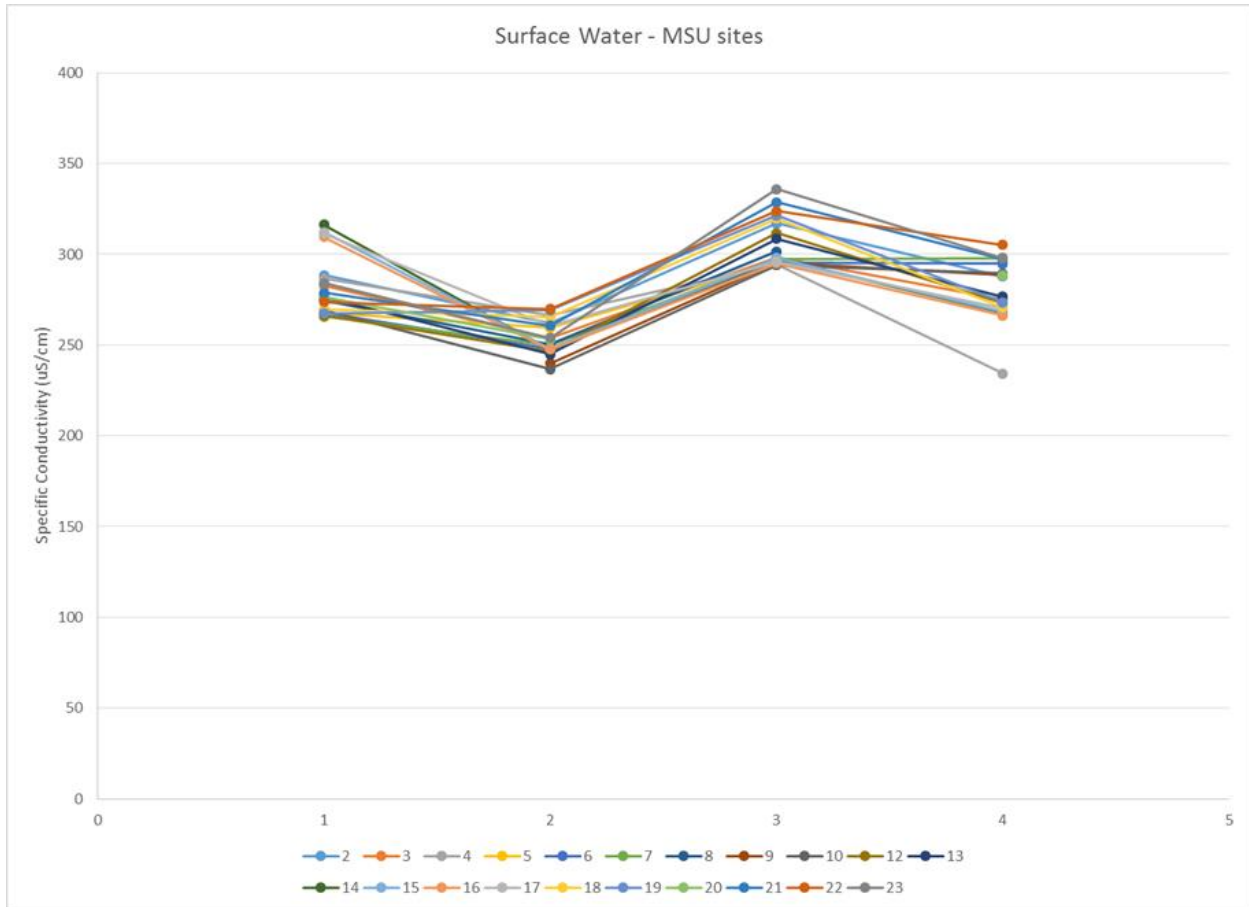
**Figure 19.** *Specific conductivity values collected by MSU from surface water at our shoreline study sites.*

The range of groundwater specific conductivity values from both the USGS and the MSU sampling events is much wider in comparison to the surface water values. USGS report groundwater specific conductivity values ranging from a minimum of 166 and a maximum of 1585 (Figure 20). USGS site 30 was particularly high in 1997 and 1998, dropping to within range of all other sites in the following years. On the other hand, some sites (10, 11, and 23) had groundwater conductivity values in the 270-300 uS/cm range, similar to surface water values. Most sites had an average specific conductivity value in the 500-650 uS/cm range. The increasing trend observed in the USGS surface water samples was not observed in the corresponding groundwater samples, which show more consistent values over time.

Groundwater specific conductivity ranged more narrowly during the MSU study than during the USGS study, with a minimum of 246 and a maximum of 877 uS/cm (Figure 21). However, most sites had conductivity values between 300 and 600 uS/cm. Exceptions include site 2, 8, 9, and 10: Site 8 had groundwater conductivity values at or below 300 uS/cm across the four 2014 sampling events, whereas sites 2, 9, and 10 stand out as having much higher groundwater conductivity across all sampling events.

The average groundwater specific conductivity across MSU sites and sampling events was 474 uS/cm, showing no change in groundwater conductivity values over time relative to the earlier USGS study.

Sites associated with the Camp Curnalia area (Figure 13) do not show a marked decrease in groundwater specific conductivity values (Table 8), as might be expected as a result of rerouting household waste away from on-site septic systems. Between 1997 and 2000, the average groundwater specific conductivity value at USGS site 24 was 423 uS/cm; whereas the average groundwater specific conductivity value at the associated MSU site 23 was 464 in 2014. There seems to be an increasing trend at USGS 23/MSU 22 as well, increasing from an average of 268 to 433 uS/cm between the two studies. However due to the many sources that contribute to groundwater specific conductivity the effects of the sewer system transition might not be evident in this temporal analysis.

*Table 8. Comparison of average specific conductivity values from the USGS and MSU studies in the Camp Curnalia area along with periods averaged for each.*

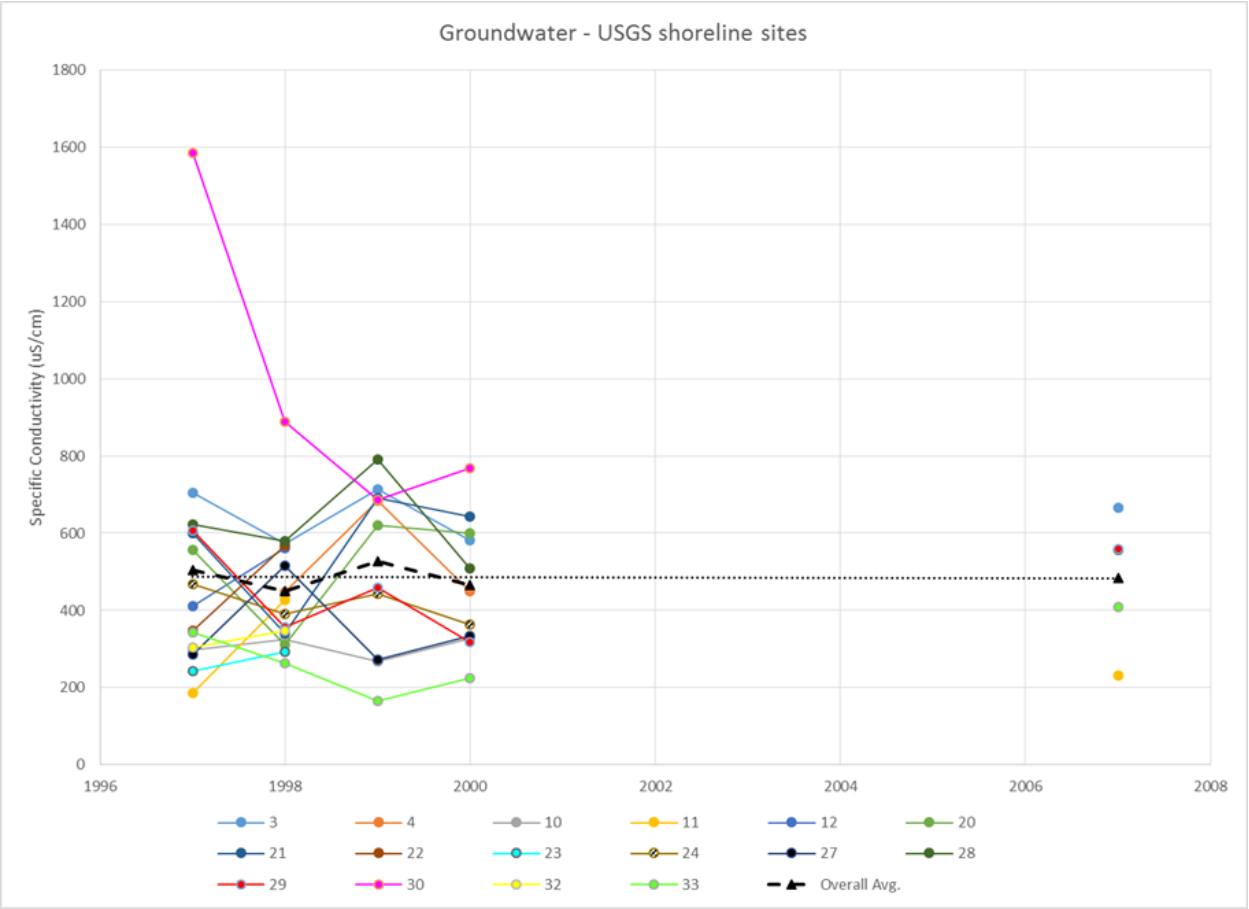| Site Number | Period Averaged | Surface water (uS/cm) | Groundwater (uS/cm) |
|---|---|---|---|
| USGS-23 | 1997-1998 | 260.3 | 268.0 |
| USGS-24 | 1997-2000 | 269.0 | 423.7 |
| USGS-29 | 1997-2000 | 273.3 | 451.8 |
| MSU-22 | 2014 | 289.3 | 433.0 |
| MSU-23 | 2014 | 291.2 | 464.0 |

*Figure 20*. *Average annual specific conductivity values collected by USGS from groundwater at their shoreline study sites. Overall average from all sites per year are shown with black triangles. Linear regression trendline is shown (dotted).*
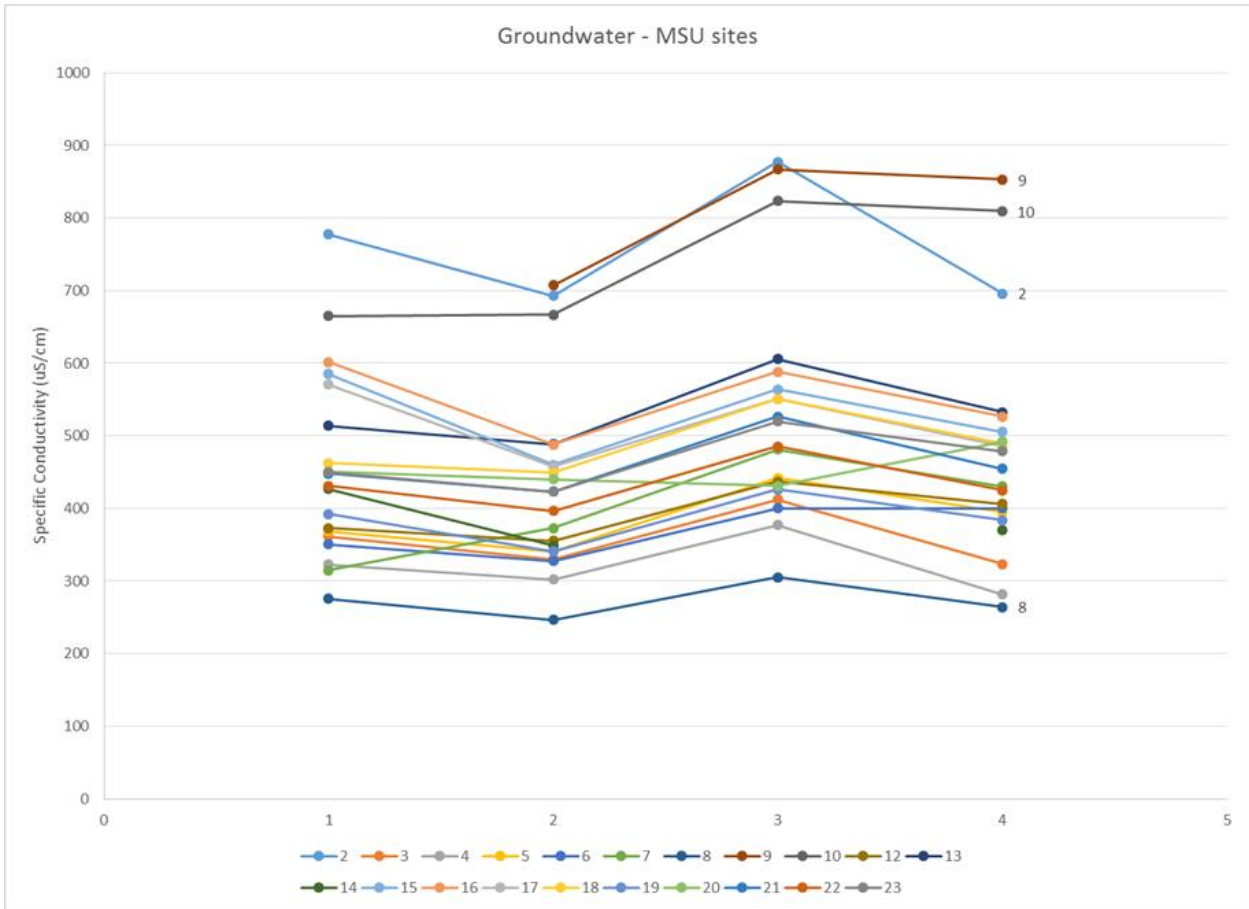
***Figure 21****. Specific conductivity values collected by MSU from groundwater at our shoreline study sites.*

The USGS also collected specific conductivity data from the north and south basin of Higgins Lake between 1995 and 2000. Average monthly values for conductivity show a slightly increasing trend over their study timeline (Figure 22). Comparing the surface water data from the USGS shoreline sites to their deep basin values, conductivity in the deep basin is slightly lower than at the shoreline sites (Figures 12 and 16). This is likely due to the relatively greater influence groundwater has in the nearshore area in comparison to the deep basins.
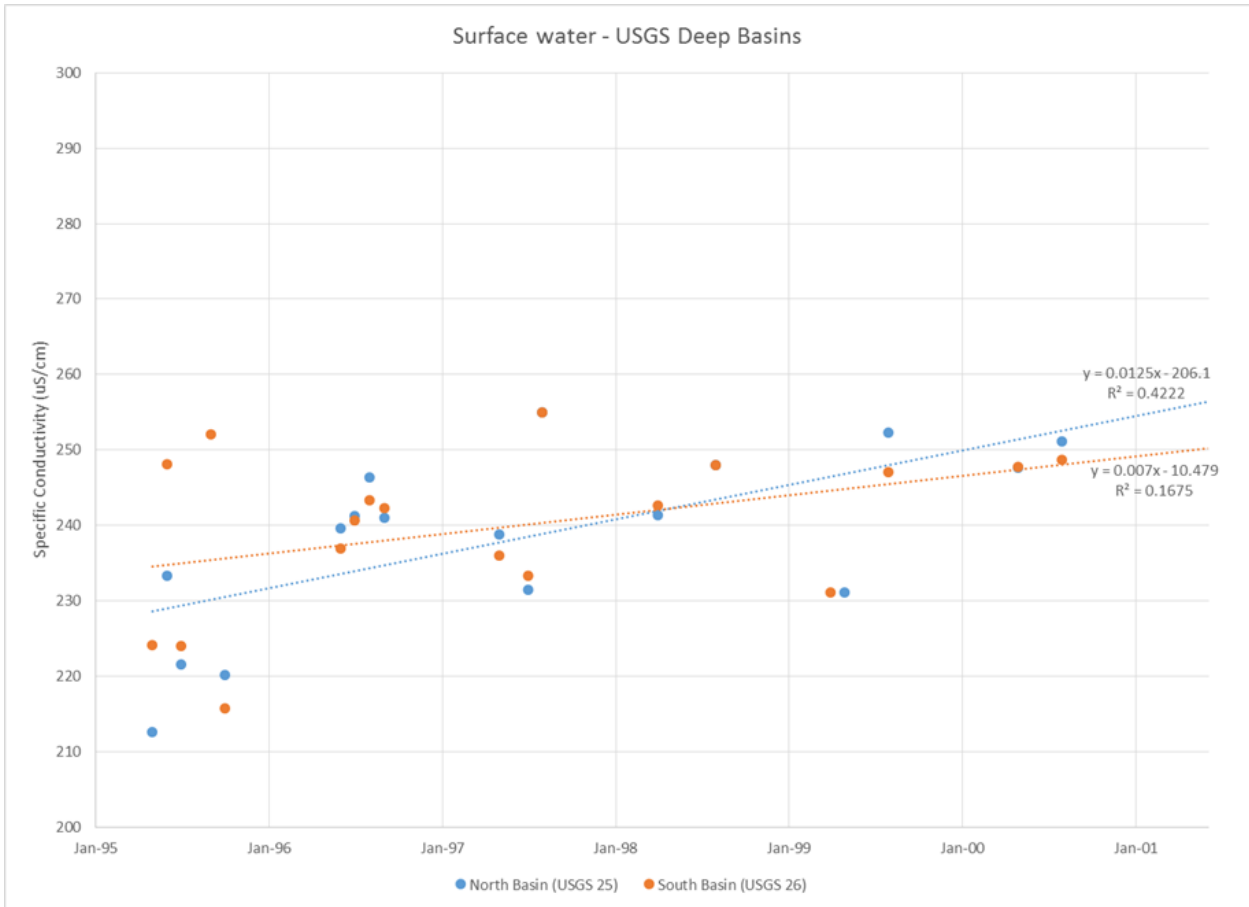
*Figure 22.* *Average monthly specific conductivity values collected by USGS at North Basin (USGS site 25) and South Basin (USGS site 26) deep water locations between 1995 and 2000. Linear regression trendline is shown (dotted) with associated equations and fit statistics.*

We also conducted an early morning shoreline survey on July 18, 2013. During this survey, we affixed our InSitu SmarTROLL multiparameter data sonde to our boat and collected measurements every 10 seconds recording dissolved oxygen and specific conductivity from the surface water along our boat path (Figure 23). An early morning survey was conducted to record values of dissolved oxygen prior to daytime photosynthesis, giving a better indication of total biotic oxygen demand.

This high-resolution spatial data shows that within the narrow range of specific conductivity values (approximately 255-278 uS/cm), typical of Michigan inland lakes (Martin & Soranno 2006), there are areas where specific conductivity abruptly shifts to higher concentrations (Figure 24). For instance, there seems to be a sudden increase in surface water specific conductivity between USGS site 4 and MSU site 19. Importantly, these shifts from low to high conductivity are not random, and remain high (or low) for a significant length of the boat track. In another example, when we turned into deeper water to go around Treasure Island, the specific conductivity of the surface water

quickly dropped to lower levels. Then, as we approached the shoreline of the island, the specific conductivity levels rose again.

These fluctuations of specific conductivity also coincided inversely ($r$ = -0.74) with decreases and increases in dissolved oxygen (Figure 25). This supports the hypothesis that higher specific conductivity values are at least partly sourced by septic system discharge into the lake, which also provides nutrients to support increased biological activity and thus reduces dissolved oxygen via respiration.

Further supporting this hypothesis, the portion of this survey with the lowest observed specific conductivity values is along the shoreline of Camp Curnalia, where wastewater is managed via a sewer system rather than via individual septic tanks. No other section of the shoreline showed such consistently low conductivity values--with correspondingly high dissolved oxygen values.
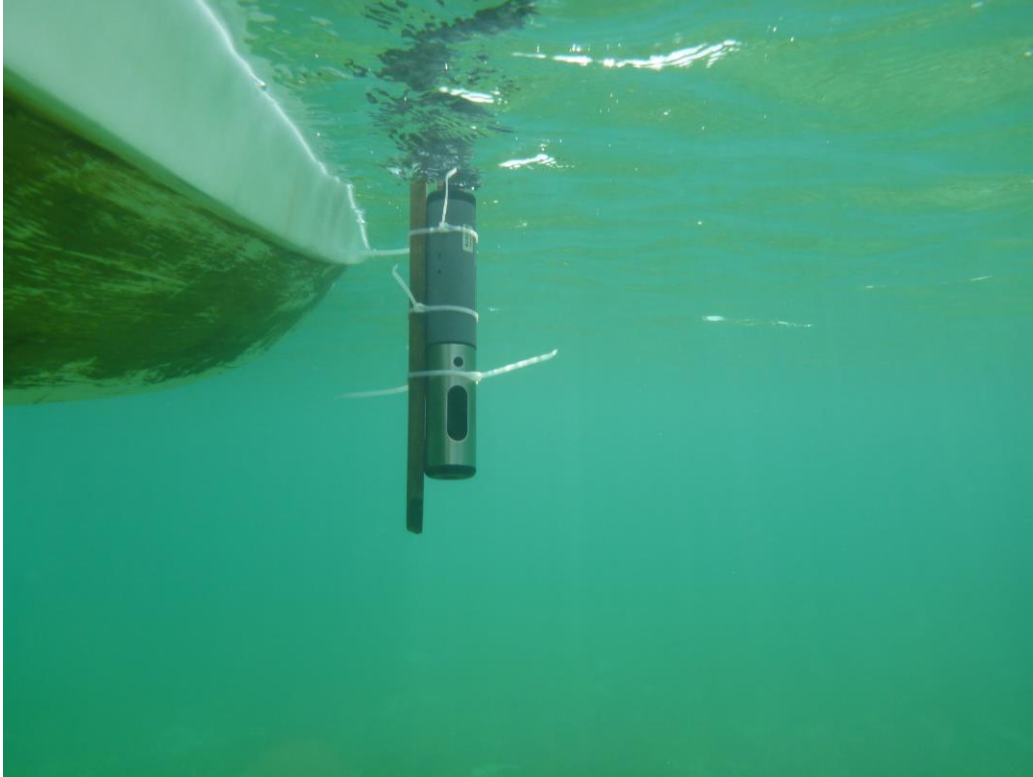
*Figure 23. Photographs taken in the field during the early morning shoreline specific conductivity and dissolved oxygen survey. A) shows attachment of multi-parameter data sonde to boat. B) shows below water sonde set-up.*

***Figure 24.*** *Map of measured surface water specific conductivity on July 18, 2013. Color bar represents 10 quantile groups.Top panel shows complete dataset. Bottom panel shows close-up of USGS/MSU site 4/19 area and boat path away from shoreline out towards Treasure Island. Sampling sites are numbered and shown as in Figure 1: USGS as triangles and MSU as circles.*

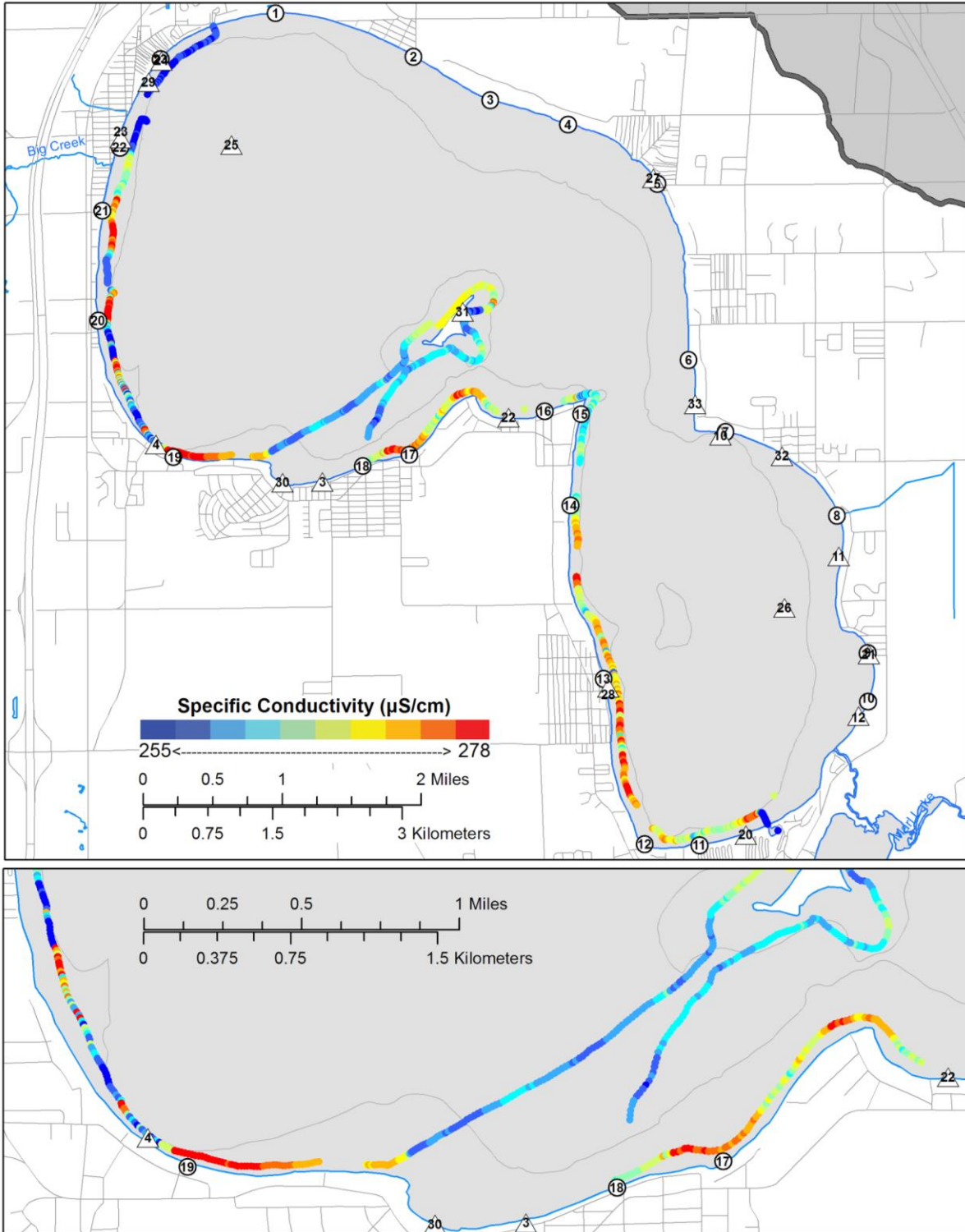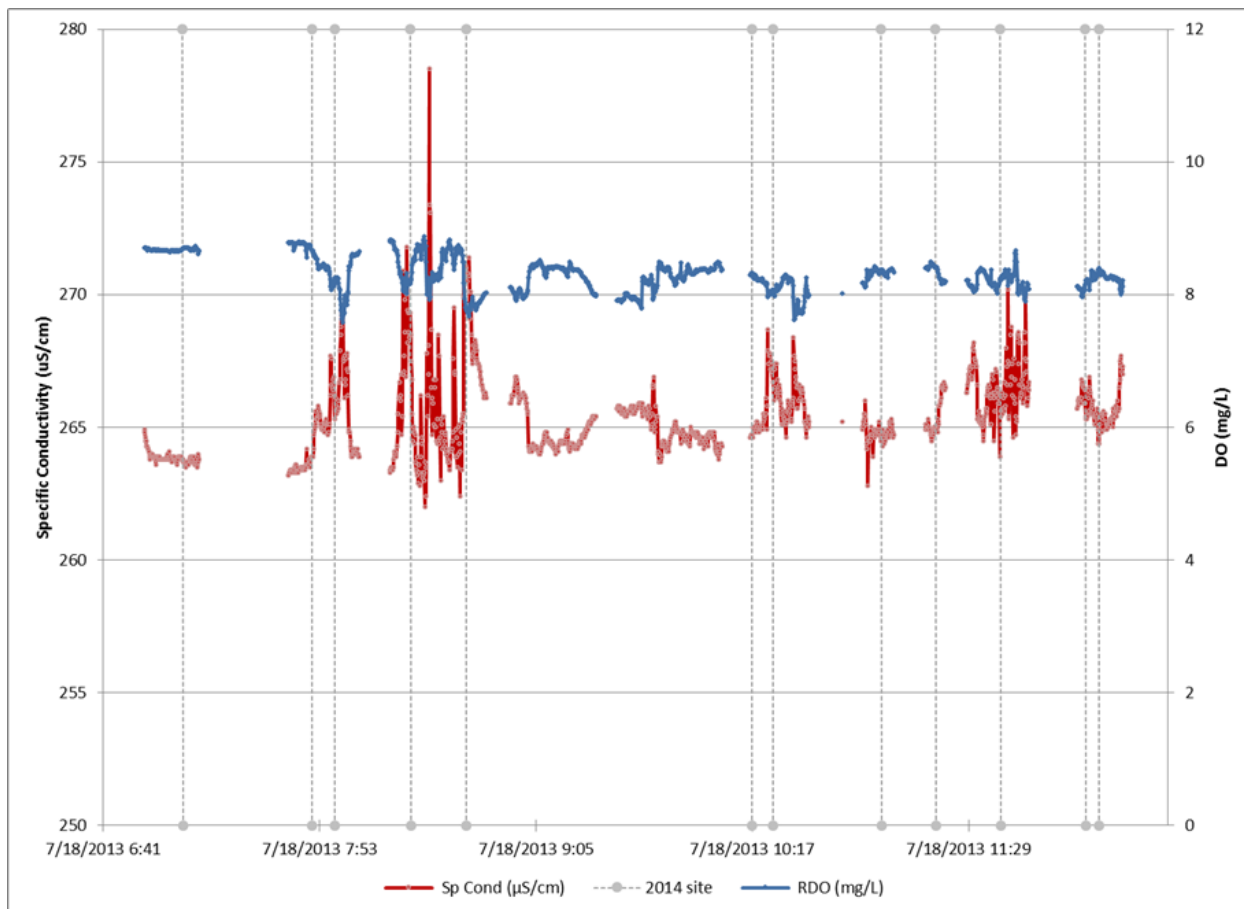**Figure 25**. *Dual-axis plot comparing specific conductivity and dissolved oxygen measured during early morning shoreline survey July 18, 2013. Location of MSU installed sites are indicated with vertical dashed grey lines. Note, the survey started at the North State Park and finished at the South State Park.*

# Chloride (Cl)

## Temporal Trends

Increasing chloride concentrations are of concern in lakes globally (Dugan et al. 2017), and Higgins Lake is no exception. In general, Cl concentrations in Higgins Lake surface water have not reached levels of ecological concern, but do indicate a general increase over time. Particularly affected are sites 24 and 29, in the 1995-2000 USGS surface water dataset (Figure 26), which also had the highest specific conductivity values. The paired MSU sites (22 and 23) are similarly high in the 2014 data, along with site 21 and site 2 (Figure 27). These sites are both located in highly developed areas.

Sources of Cl to freshwaters of this region include salts for road de-icing and water softener salt. Groundwater is a primary delivery mechanism for both of these Cl sources, as evidenced by the fact that Cl concentrations in groundwater greatly exceed

those of surface water (Figures 28 and 29). Road salt would be expected to be used most prominently on major roads, such as US-127 and those that circumnavigate the lake. This is the case for MSU sites 20-23, and to a lesser degree sites 19, and 2-5. Most of those sites do have high Cl concentrations, in both surface and groundwater.
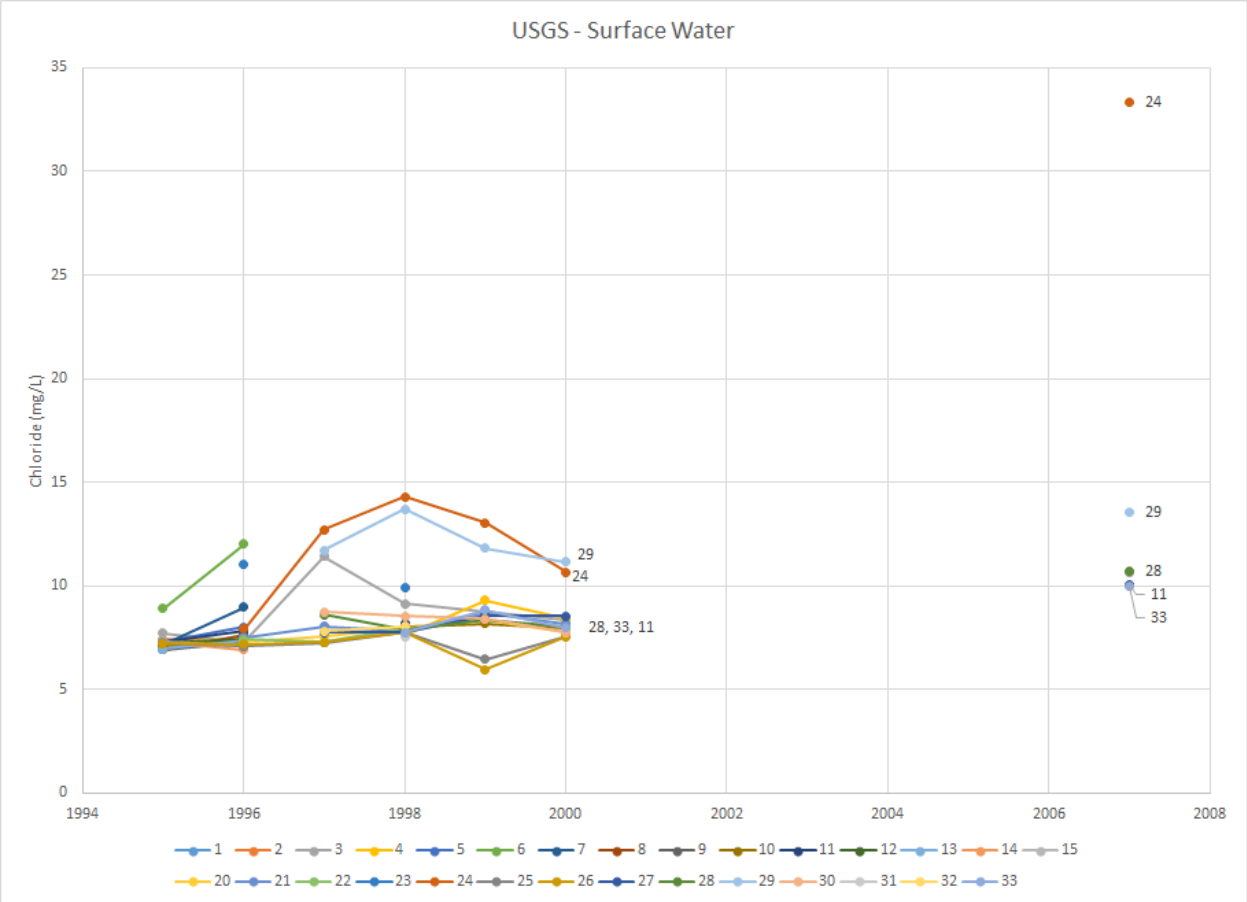


*Figure 26*. Average annual chloride values collected by USGS from surface water at their shoreline study sites.
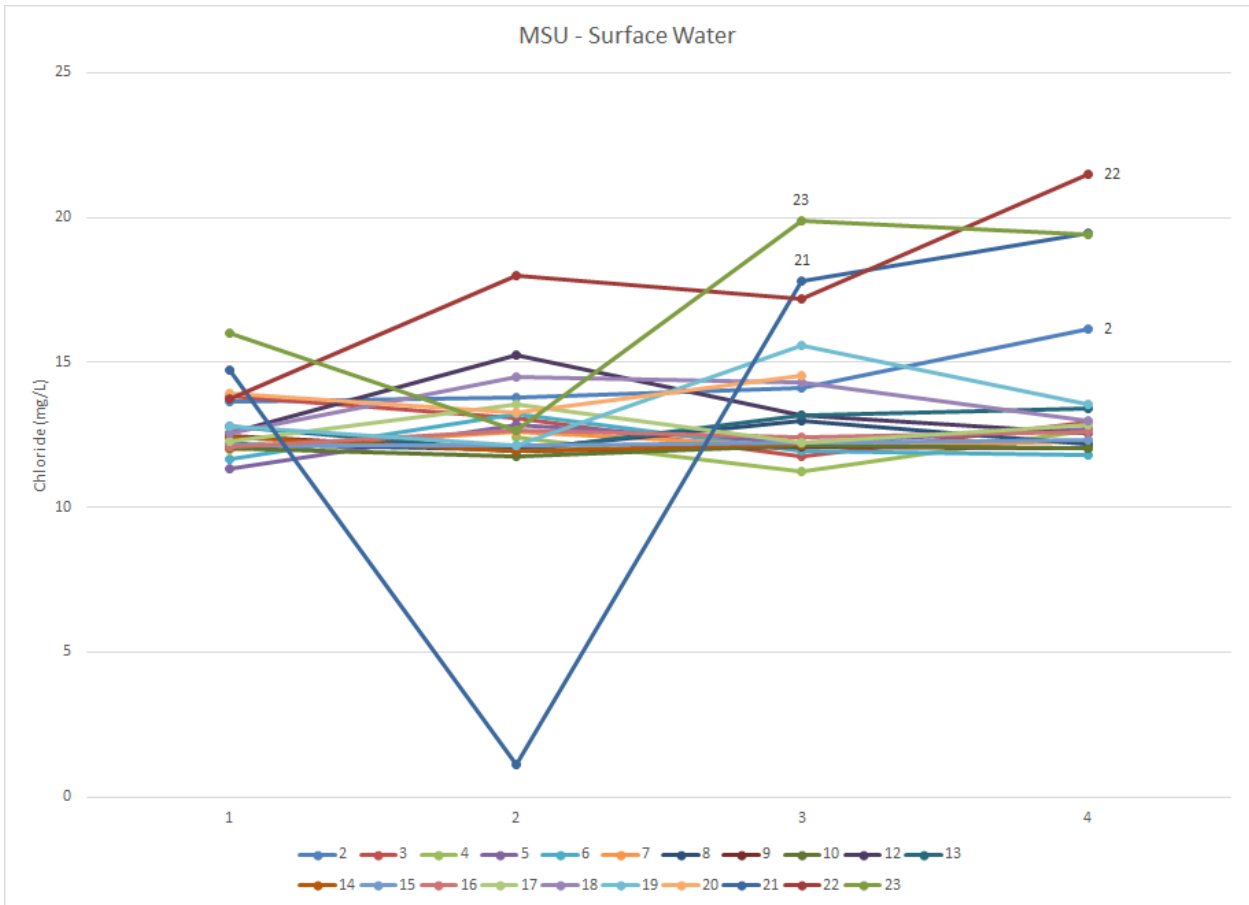
*Figure 27.* Chloride values collected by MSU from surface water at our shoreline study sites.
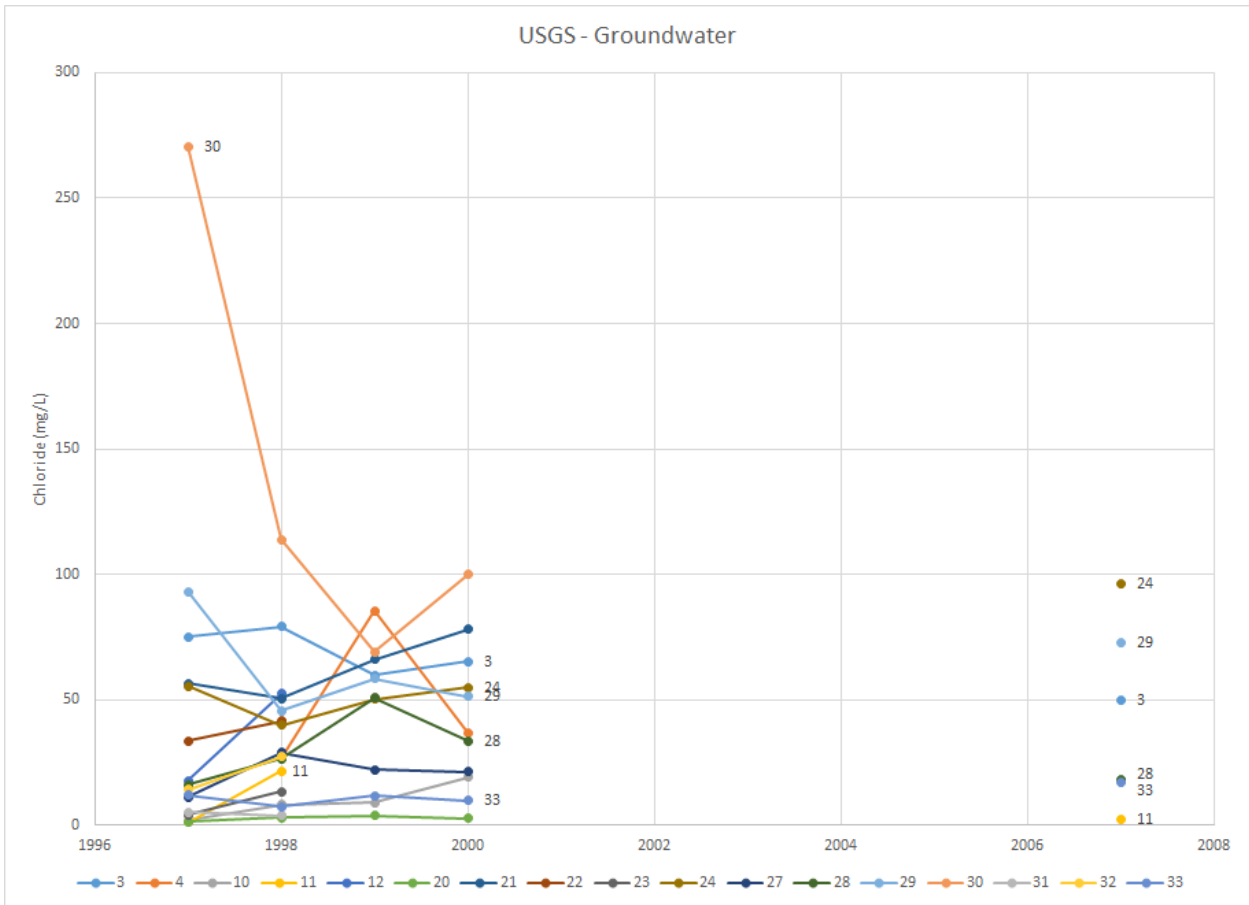
*Figure 28*. Average annual chloride values collected by USGS from groundwater at their shoreline study sites.
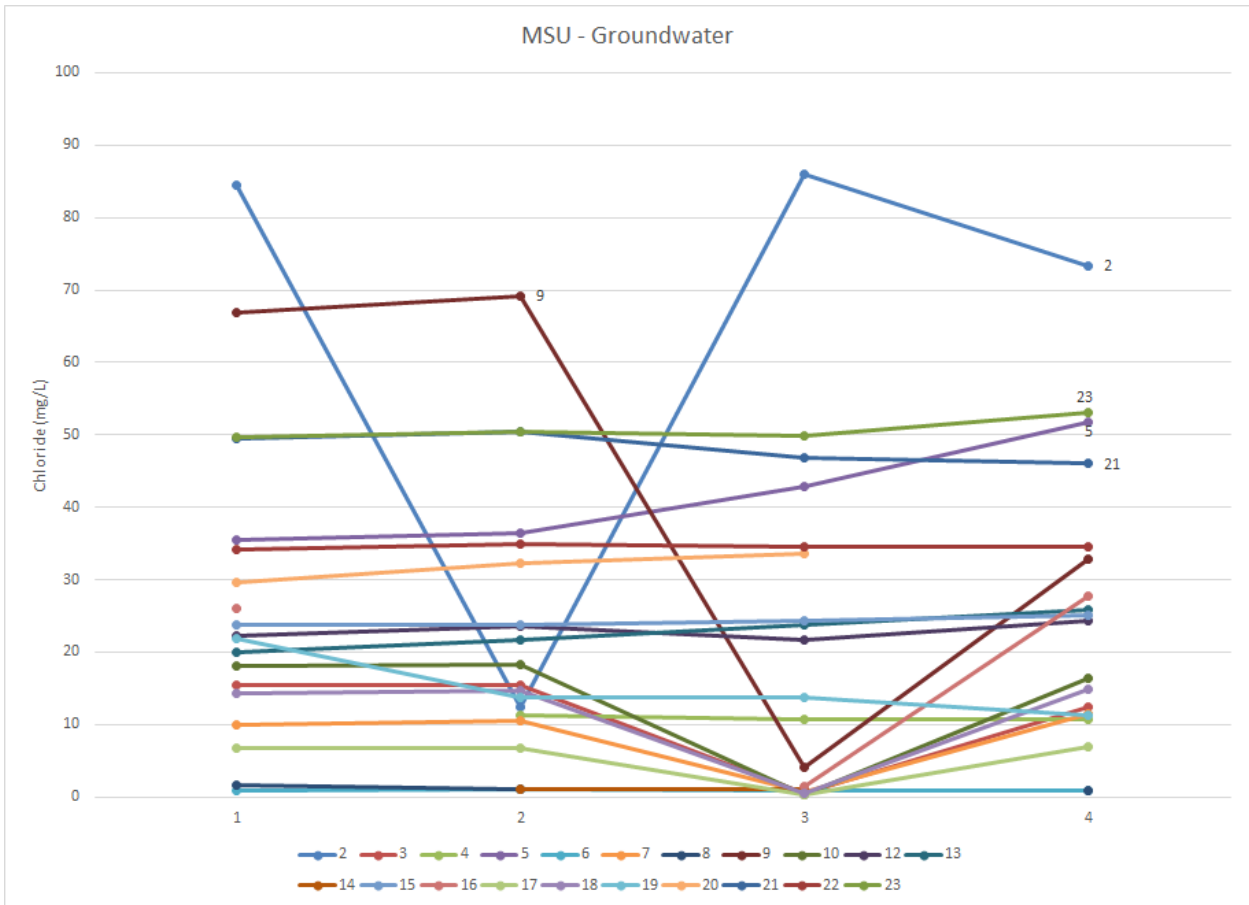
***Figure 29***. *Chloride values collected by MSU from groundwater at our shoreline study sites.*

Overall Cl concentrations in SW increased from 8.3 to 13.2 ug/L from the late 1990's to 2014, but decreased in GW over this same time span (Table 9). The change in near shore surface water concentrations is likely robust, reflecting comparable methods and analytical procedures between the two studies. Again due to sampling methodology differences, interpreting the decrease in groundwater Cl concentration may include artifacts from different sample collection techniques.

***Table 9***. *Summary of overall near shore surface water (SW) and groundwater (GW) chloride average concentrations between USGS and MSU studies*

| Study | Years | Location | Concentration (ug/L) |
|-------|-------|----------|----------------------|
| USGS | 1997-2000 | SW | 8.25 |
| USGS | 1997-2000 | GW | 40.3 |
| MSU | 2014 | SW | 13.2 |
| MSU | 2014 | GW | 23.8 |

Similarly to specific conductivity, and in contrast to B (discussed below), $NO_3+NO_2$, and TP, Cl concentrations in the Camp Curnalia nearshore have not responded as strongly to the wastewater treatment system (Table 10). This could be because Cl inputs are dominated by road salt use--however this study did not attempt to test this hypothesis.

*Table 10 Comparison of average chloride values from the USGS and MSU studies in the Camp Curnalia area along with periods averaged for each.*

| Site Number | Period Averaged | Surface water (mg/L) | Groundwater (mg/L) |
|---|---|---|---|
| USGS-23 | 1997-1998 | 10.4 | 8.7 |
| USGS-24 | 1997-2000 | 15.3 | 59.3 |
| USGS-29 | 1997-2000 | 12.4 | 64.3 |
| MSU-22 | 2014 | 17.6 | 34.6 |
| MSU-23 | 2014 | 17.0 | 50.7 |

# Boron (B)

## Summer 2014

Boron is a common component in agricultural fertilizers, for its role as a micronutrient and a pesticide, as well as in laundry soaps and detergents as a whitening agent. Boron has been used as a tracer to locate areas receiving effluent from these anthropogenic sources through surface water and groundwater pathways. The EPA removal action limit (RAL) is 900 ug/L in drinking water, above which adverse health effects are associated.

Boron concentrations observed during the 2014 MSU study and summarized in Table 11 were low in comparison to concentrations found in septic tank effluent (35-318 ug/L, Richards et al. 2016) and those observed at sites influenced by septic systems in a 2004 study by USGS in Northern Indiana (84-387 ug/L, Buszka et al. 2007). All samples taken during the MSU study were well below the EPA RAL.

Average boron concentrations were very similar in groundwater and surface water samples during the 2014 MSU study, with an overall mean of 18 ug/L and 11 ug/L, respectively. However, average boron concentrations in groundwater were elevated at sites 5, 9, 12, and 15 relative to surface water samples by between 19 to 69 ug/L. Site 3 had the highest observed boron concentrations (92 ug/L), but site 12 had

the highest average groundwater concentration (80 ug/L) and site 2 had the highest average surface water concentration (16 ug/L). Site 14 had the lowest boron concentrations in groundwater and surface water, 3.8 and 7.6 ug/L, respectively.

*Table 11.* *Summary statistics for Boron (B) per site from groundwater samples. Units vary by constituent, reported as ug/L (equivalent to parts per billion, ppb). n=number of samples analyzed from site. Max=maximum concentration observed at site. Min=minimum concentration observed at site.*

| | Groundwater B (ug/L) | | | | Surface Water B (ug/L) | | | |
|---|---|---|---|---|---|---|---|---|
| Site | n | Max | Mean | Min | n | Max | Mean | Min |
| 2 | 5 | 18 | 12 | 5.9 | 5 | 22 | 16 | 12 |
| 3 | 6 | 92 | 19 | 11 | 6 | 41 | 14 | 10 |
| 4 | 5 | 6.4 | 5.7 | 5.2 | 5 | 13 | 11 | 11 |
| 5 | 4 | 49 | 37 | 19 | 4 | 8.8 | 8.6 | 8.3 |
| 6 | 4 | 8.5 | 8.0 | 7.6 | 5 | 11 | 11 | 10 |
| 7 | 4 | 23 | 21 | 18 | 4 | 12 | 12 | 11 |
| 8 | 4 | 11 | 10 | 8.7 | 4 | 17 | 13 | 11 |
| 9 | 5 | 72 | 67 | 64 | 5 | 12 | 11 | 11 |
| 10 | 4 | 15 | 13 | 12 | 4 | 8.4 | 8.1 | 7.8 |
| 12 | 4 | 87 | 80 | 73 | 4 | 12 | 11 | 11 |
| 13 | 5 | 12 | 11 | 10 | 5 | 12 | 10 | 7.9 |
| 14 | 2 | 4.0 | 3.8 | 3.5 | 3 | 7.8 | 7.6 | 7.2 |
| 15 | 6 | 33 | 30 | 28 | 5 | 12 | 11 | 11 |
| 16 | 3 | 8.8 | 8.0 | 7.1 | 4 | 11 | 11 | 10 |
| 17 | 5 | 12 | 10 | 9.8 | 5 | 11 | 11 | 11 |
| 18 | 4 | 9.5 | 9.3 | 9.2 | 4 | 12 | 11 | 10 |
| 19 | 4 | 17 | 10 | 6.2 | 4 | 12 | 9.2 | 7.4 |
| 20 | 3 | 7.8 | 7.1 | 6.2 | 3 | 8.7 | 8.4 | 8.1 |
| 21 | 5 | 8.1 | 6.6 | 4.2 | 5 | 8.1 | 8.0 | 7.8 |
| 22 | 5 | 8.9 | 8.1 | 7.4 | 5 | 12 | 11 | 10 |
| 23 | 5 | 6.3 | 6.0 | 5.8 | 5 | 10 | 10 | 9.9 |

## Temporal Trends

Overall, surface water boron concentrations around the lake have changed very little since the mid-1990s. The USGS collected boron samples at their sites intermittently from surface water between 1995 and 2000 and during summer months from groundwater between 1997 and 2000. Average annual boron concentrations across this time period varied narrowly between 7 and 22 ug/L (Figure 30), with all sites showing similar trends. MSU surface water samples collected during the summer of 2014 show little change in boron concentration, varying between 7 and 22 ug/L, except for a higher value collected at site 3 after the 4th of July holiday (Figure 31).

Boron concentrations in groundwater varied more widely than surface water concentrations. All samples from MSU sites were below 100 ug/L (Figure 33); however, USGS sites 3, 21, and 27 had occasions with annual average concentrations above 100 ug/L (Figure 32).

MSU sites 9 and 5 are closely located with USGS sites 21 and 27, respectively, and were among the few sites from the MSU study that had higher boron concentrations. MSU site 9 shows that groundwater boron concentrations have dropped to between 65-70 ug/L, about half of what they were in 2000 in the same area. USGS site 27 had been showing an increasing boron concentration in the late-1990s but then dropped to a low concentration in 2000. MSU site 5 shows that boron concentrations in the groundwater of this area have remained low. However, due to the highly heterogeneous nature of groundwater flowpaths, it is possible that concentrations taken from another nearby location could reflect a very different character.



*Figure 30*. *Average annual boron values collected by USGS from surface water at their shoreline study sites.*

**Figure 31**. Boron values collected by MSU from surface water at our shoreline study sites.
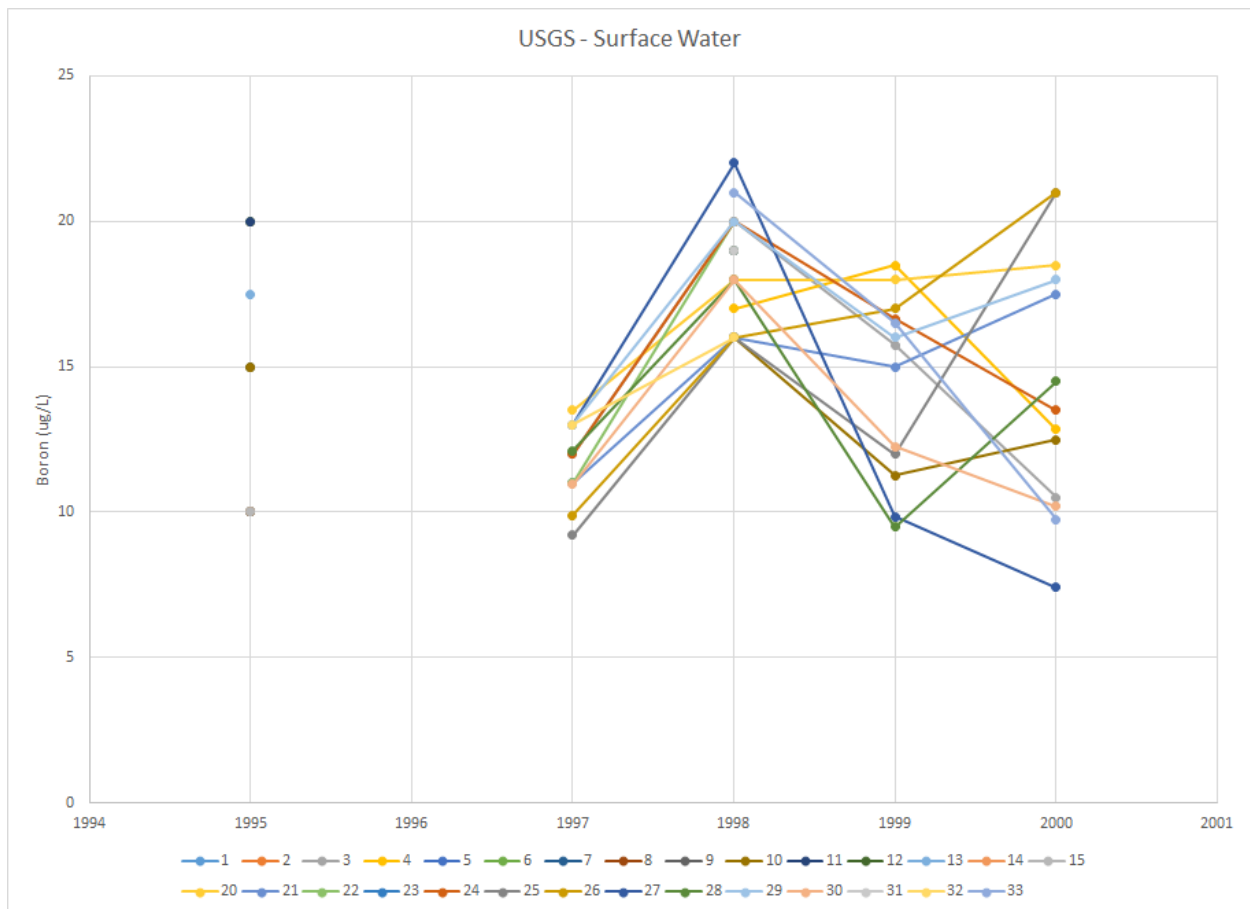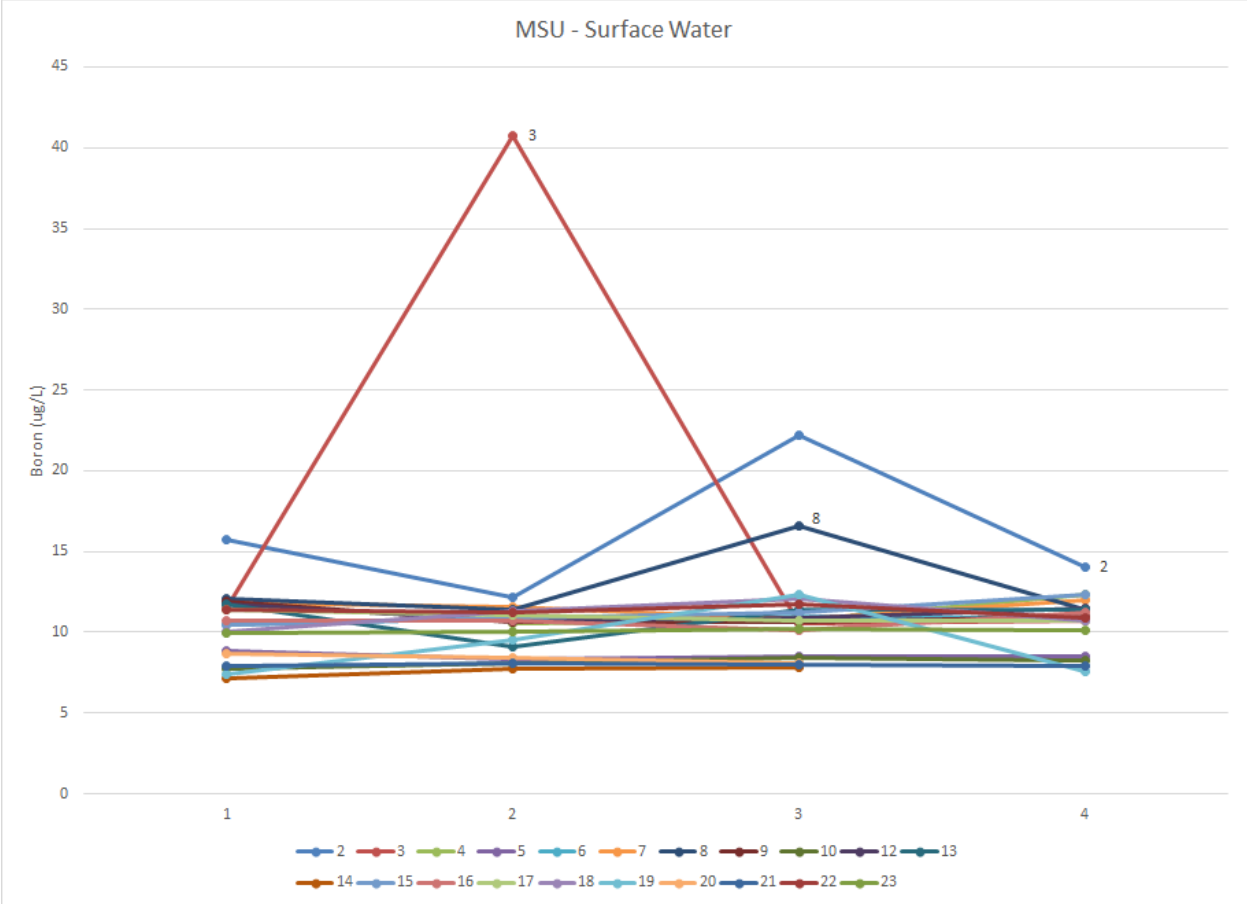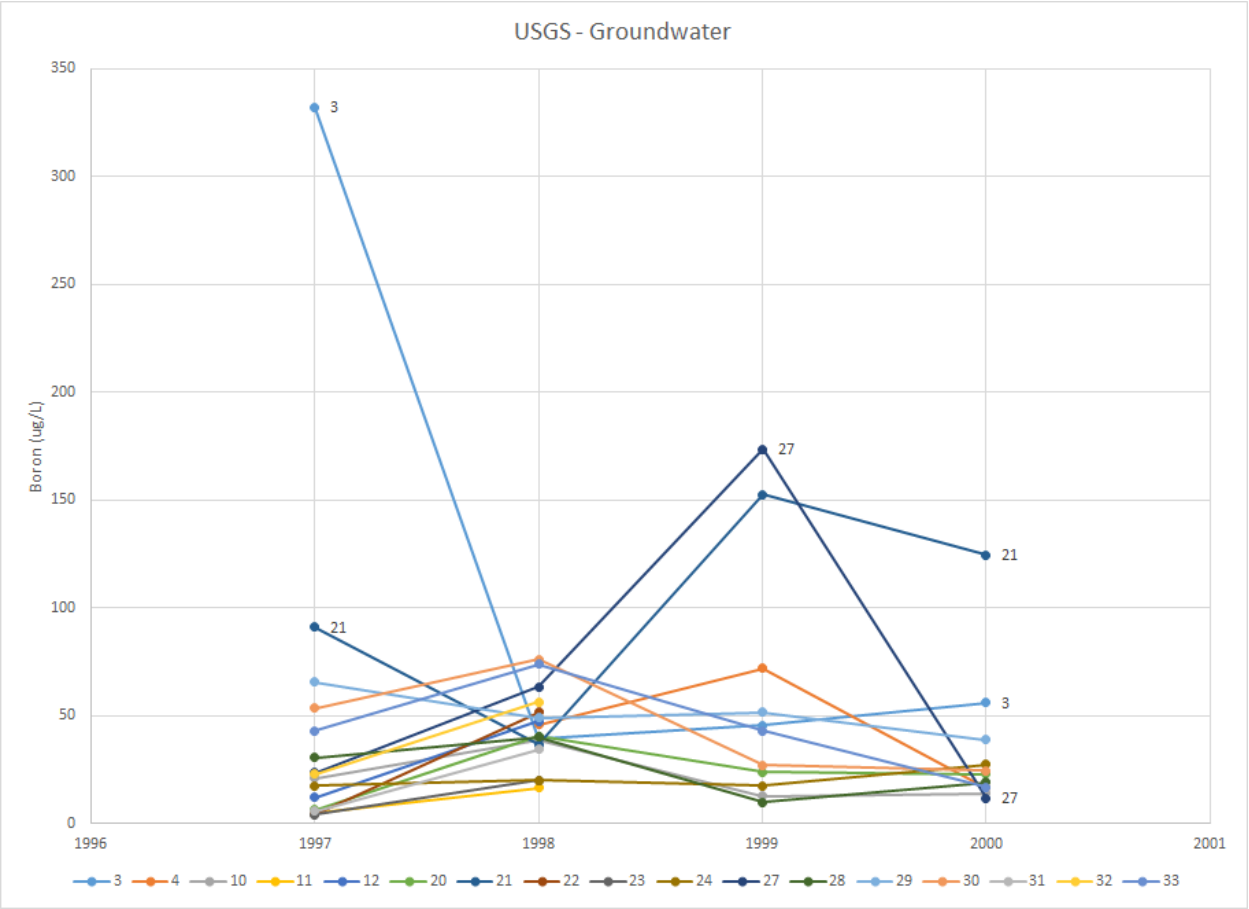
*Figure 32*. *Average annual boron values collected by USGS from groundwater at their shoreline study sites.*
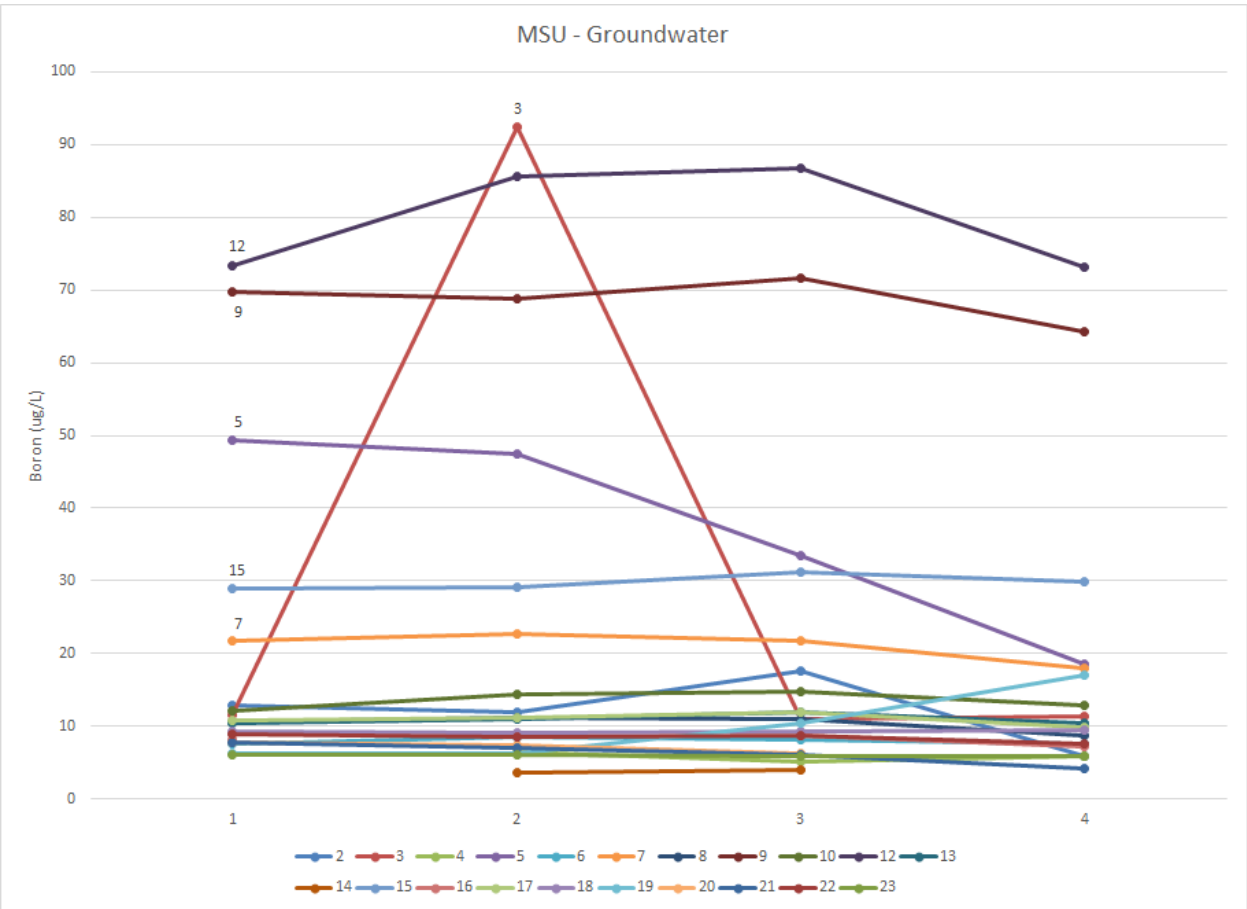
*Figure 33. Boron values collected by MSU from groundwater at our shoreline study sites.*

Lake-wide average concentrations of near-shore surface water concentrations of boron have declined approximately 26% since the late 1990s (Table 12). This may reflect the change in overall use human patterns of boron, i.e. a decline a boric acid use in consumer products. Notably the difference between USGS and MSU-sampled groundwater B concentrations is much greater than surface water, with a decline of 38% since the late 1990s. This could reflect the aforementioned differences in groundwater sampling procedures and human uses, or it may simply indicate a greater proportional decline in B sources via groundwater relative to whole-lake concentrations due to in-lake cycling and residence time of water in Higgins Lake (roughly 5 years).

*Table 12. Summary of overall near shore surface water (SW) and groundwater (GW) boron average concentrations between USGS and MSU studies*

| Study | Years | Location | Concentration (ug/L) |
|-------|-------|----------|----------------------|
| USGS | 1995-2000 | SW | 14.9 |
| USGS | 1997-2000 | GW | 47.9 |

| | | | |
|---|---|---|---|
| MSU | 2014 | SW | 11.0 |
| MSU | 2014 | GW | 19.8 |

Concentrations of boron in groundwater near Camp Curnalia have declined much more substantially, while surface water concentrations closely follow whole-lake patterns (Table 13). For the USGS-23/MSU-22 pairing (Figure 13), B concentrations declined by 30% relative to USGS values in the late 1990s. Concentrations declined by 71% for the USGS-24/MSU-23 pairing. This supports the hypothesis that B inputs sourced from septic systems have decreased due to the sewer system installed in 2009 in that area of the lake.

*Table 13*. Comparison of average boron values from the USGS and MSU studies in the Camp Curnalia area along with periods averaged for each.

| Site Number | Period Averaged | Surface water (ug/L) | Groundwater (ug/L) |
|---|---|---|---|
| USGS-23 | 1997-1998 | 16.0 | 12.0 |
| USGS-24 | 1997-2000 | 15.4 | 20.6 |
| USGS-29 | 1997-2000 | 16.8 | 51.3 |
| MSU-22 | 2014 | 11.3 | 8.4 |
| MSU-23 | 2014 | 10.1 | 6.0 |

# Statistical Relationships between Water Quality and Septic Systems

We analyzed the relationship between water chemistry parameters and measures of septic tank influence using simple and multiple linear regressions. Parameters included in the regression models are:

- Groundwater flow velocity is a direct measure of groundwater inflow at each sampling site. These values are calculated from seepage meter measurements taken in August 2014.
- Hydraulic gradient is a measure of change in groundwater elevation between two points. We used our groundwater elevation map (Figure 5) to calculate the hydraulic gradient 400m and 1000m upgradient from our sampling

piezometers. This helps estimate the strength of subsurface transport through groundwater flowpaths.

- Septic count is an estimate of the number of septic systems in the upgradient flowpath taken from our statewide model of septic systems (Luscz et al. 2015).
- Septic flux takes hydraulic gradient multiplied by septic count to estimate septic system contributions from the specified flowpath length (400m or 1000m).
- Parcel count and parcel flux are calculated identically to septic count and flux but uses the number of upgradient land parcels (provided by Roscommon County). Because our statewide septic map is based on remotely sensed data and US Census data to use over larger spatial extents, we expect parcels to more accurately reflect septic contributions for the Higgins Lake area.

**Table 14.** *Results from simple linear regression analyses. Significance level from p-values indicated by asterisk: *** p-value<0.001, ** p-value<0.01, * p-value<0.05, "ns" not significant. Total phosphorus (TP), nitrate + nitrite ($NO_3 + NO_2$), ammonia ($NH_3$) and boron (B) are included in this analysis.*

| | | TP | | $NO_3+NO_2$ | | $NH_3$ | | B | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | GW | SW | GW | SW | GW | SW | GW | SW |
| Groundwater Velocity | | ns | *** | ns | * | *** | * | ** | *** |
| Hydraulic Gradient | 400 | *** | ** | ns | ns | ns | ** | ns | ns |
| | 1000 | ** | ** | ns | ns | ns | * | ns | ** |
| Septic Count | 400 | ns | *** | ns | ns | *** | * | ns | ns |
| | 1000 | ns | *** | ns | ns | *** | * | ns | ns |
| Parcel Count | 400 | ns | ns | ns | ns | *** | * | * | ns |
| | 1000 | ns | ns | ns | ns | * | * | ** | ns |
| Parcel Flux | 400 | ** | ** | ns | * | ns | ** | ns | ns |
| | 1000 | * | ns | ns | ns | ns | * | ns | ns |
| Septic Flux | 400 | *** | *** | ns | ns | ns | *** | ns | ns |
| | 1000 | *** | *** | ns | ns | ns | * | ** | ns |

*** p-value<0.001     ** p-value<0.01     * p-value<0.05     "ns" not significant

## Phosphorus

Groundwater phosphorus concentrations were significantly related to hydraulic gradient and both flux parameters, but were not significantly related to either septic count or parcel count. The flux parameters are calculated using both septic or parcel counts (as appropriate) and hydraulic gradient. Therefore, it is likely that hydraulic gradient is driving the relationship with the flux parameters. Hydraulic gradient 400m had the highest explanatory power at 14%.

Surface water phosphorus concentrations were significantly related to septic counts and both measures of subsurface input (hydraulic gradient and groundwater flow velocity). Septic flux was also significantly related to surface water phosphorus, with explanatory power of 21% at the 400m distance and 11% at the 1000m distance.

We investigated these simple regression results further using multiple linear regression, which includes multiple parameters to explain variations in the water chemistry parameter. Both groundwater and surface water phosphorus concentrations had highly significant models ($p < 0.001$) when subsurface transport was coupled with estimates of septic or parcel inputs and higher explanatory power: 24% for groundwater and 27% for surface water.

Based on this analysis, we conclude that both groundwater and surface water phosphorus concentrations are related to septic sources and subsurface transport mechanisms, explaining ~30% of the variation in the data.

## Nitrogen ($NO_3$ + $NO_2$)

Groundwater nitrate-nitrite ($NO_3 + NO_2$) concentrations were not significantly related to any of the parameters tested in simple regressions. Multiple linear regression analyses of $NO_3 + NO_2$ did not result in significant models either.

Surface water $NO_3 + NO_2$ concentrations were related to groundwater flow velocity and parcel flux at low significance levels ($p < 0.05$), explaining only 7% of the variation in the data. Multiple linear regression approach did not produce any significant models.

Thus, nitrate-nitrite appear to have little relation to septic sources and subsurface transport.

## Nitrogen ($NH_3$)

We include analysis of ammonia ($NH_3$) as an additional measure of nitrogen. This form of nitrogen resulted in more significant relationships in the regression models. Groundwater flow velocity was significantly related to groundwater and surface water $NH_3$ concentrations. However, the other measure of subsurface transport (hydraulic gradient) was only significantly related to surface water $NH_3$ concentrations. Septic count and parcel count over both distances were significantly related to groundwater

and surface water $NH_3$. The flux parameters were only significantly related to surface water $NH_3$ concentrations. Parcel count at 400m had the highest explanatory power at 12% for groundwater $NH_3$ concentrations.

Looking into the multiple regression results, groundwater $NH_3$ concentrations were significantly related to hydraulic gradient and parcel count at 400m, explaining 23% of the variation in the $NH_3$ data. Multiple regression models for surface water $NH_3$ were less strong, explaining only about 10% of the variation.

We conclude that ammonia had significant relationships with septic sources and subsurface transport, explaining ~20% of the variation in the data.

## Boron (B)

Boron concentrations in both surface water and groundwater were significantly related to groundwater flow velocity. Explanatory power for this regression model was low for groundwater concentrations (9%) but increased to 20% for surface water concentrations. Other significant results from simple linear regression models for boron had low explanatory power, approximately 5%.

Multiple regression analyses for groundwater boron concentrations did not reveal any models with higher explanatory power. However, boron concentrations in surface water had a significant relationship with groundwater flow velocity and septic count, explaining 23% of the variance in the data.

Based on this analysis, we conclude that groundwater flow velocity and septic count had a significant relationships with boron concentrations in surface water, explaining just over 20% of the variation in the data. Groundwater boron concentrations did not show strong relationships with the parameters we tested.

# Summary and Conclusions

We developed a new water quality dataset for Higgins Lake, significantly updating and expanding from a USGS late 1990s study. These data provide a basis for several important conclusions, and can continue to serve as a baseline for future needs. The project also serves as an opportunity to leverage other research interests and projects such as the paired use of drone imagery with fiber optic distributed temperature sensing and electrical resistivity measurements. We attempted to conduct a snail population survey for comparison to water quality and septic system data, however not enough snails were observed in the marked transects, so this aspect of the project was abandoned.

Since the late 1990s, lake water chemistry has changed dramatically for all of the major water chemistry variables, with the partial exception of $NO_3+NO_2$. Average TP

concentrations in the nearshore surface waters has increased such that, on average, this part of Higgins Lake has shifted from oligotrophic conditions in the late 1990s to mesotrophic in 2014--with the attendant ecological consequences. Specific conductivity and Cl concentrations are increasing in surface water, reflecting a continued and increasing load from sources such as road-salt. Boron concentrations are declining in both surface water and groundwaters, potentially reflecting changes use habits of B containing compounds, along with apparent reductions due to the Camp Curnalia sewer project.

The camp Curnalia sewer system installation appears to have dramatically decreased groundwater TP and $NO_3+NO_2$ concentrations and thus the inputs to the lake. In the case of TP, this resulted in lower surface water concentrations, and preserved the oligotrophic status of that section of the near shore. As might be expected, B concentrations in groundwater also declined, indicating a decline in septic system inputs to that portion of the lake. In a partial early morning dissolved oxygen and specific conductivity survey, the Camp Curnalia area had the highest DO and lowest specific conductivity, indicating higher water quality.

Differences in groundwater sampling techniques and locations limit some interpretation of changes through time. This study relied on semi-permanently installed and equilibrated piezometers, that were sampled using specific techniques to reduce sediment contamination and lake water draw-down. The prior USGS study used temporary piezometers, which disturb the sediment and may have been pumped before fully equilibrating with the subsurface.

Septic systems significantly influence $NH_3$ concentrations (loading ammonia to the nearshore) and B concentrations, as expected of a septic indicator. Septic fluxes (or the combination of septic systems and high groundwater) control groundwater TP inputs. Surface water concentrations of both TP and $NH_3$ are correlated to both groundwater inputs and septic counts. The variable most commonly related to water chemistry in both surface and groundwater is seepage rate.

We make three specific recommendations for future work: 1) keep the installed network of piezometers in place, these will provide an invaluable chance to sample the same groundwater input locations in the future, 2) continue to sample, even infrequently, at a specific set of times throughout the year, and 3) conduct early morning shoreline conductivity surveys, perhaps once per year in a similar set of conditions. This could be used to help identify failed septic systems or those in need of maintenance.

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