Assessment and compilation of water quality data for a two-dimensional water quality model of Lake Erie over a decadal time period

By

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Abstract

Lake Erie has been facing ecological impacts due in part to human activities. Over the past several decades the lake has been impacted by pollution, habitat destruction and alterations, and invasive species. Excessive phosphorus loading from both point and nonpoint sources created huge changes in productivity since the 1960s. Lake Erie also suffered from strong *Microcystis* blooms, which in turn has impacted drinking water, lake production, and fauna. In addition, the introduction of invasive dreissenid mussels in 1986 caused further impacts to system processes. This project compiles input data from 2010 for a two-dimensional water quality model that simulates the impacts of many of these stressors on Lake Erie water quality. Data from 2010 were compared with those of 1998, for which year the model was last calibrated in a previous study by Zhang (2006). A major change between the two time periods was an increase in the annual tributary phosphorus loads to Lake Erie. There was also a resulting increase in within lake phosphorus concentrations and a decrease in within lake nitrogen levels. Discussion of the use of the model was provided; however, actual model runs with the newer 2010 data were not completed due to project time constraints.

Acknowledgements

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Introduction

Lake Erie is the smallest of the Laurentian Great Lakes by volume and has faced a variety of ecological impacts due to human activities. Over the past several decades the lake has been impacted by pollution, habitat destruction and alterations, and invasive species. Lake Erie is the warmest of the Great Lakes and the most biologically productive. A dramatic increase in population and human activities within the Lake Erie basin and associated high nutrient inputs, specifically phosphorus, led to rapid eutrophication of Lake Erie beginning in the 1960s.

Under the Federal Clean Water Act of 1972 the Army Corps of Engineers was authorized to initiate the Lake Erie Wastewater Management Study (LEWMS). This study set the course for lake restoration by initiating a detailed monitoring program. The LEWMS determined the total amount of phosphorus entering the lake and helped exhibit the importance of both wastewater treatment plant effluents and land runoff (U.S. Army Corps of Engineers 1983).

Blue-green algae began causing problems with taste and odor in drinking water supplies, stressing the aquatic community, and contributing to widespread oxygen depletion within Lake Erie in the 1960s (Ohio Lake Erie Phosphorus Task Force, 2010). The total phosphorus loads of more than 25,000 metric tons per year were identified as the cause of the excess algae growth (Ohio Lake Erie Phosphorus Task Force, 2010).

A target load of 11,000 metric tons per year was established for Lake Erie in the late 1970s after modeling studies of the relationship among total phosphorus loading to the lake, concentrations in the lake, algal densities, and oxygen depletion rates within the central basin (Baker et al. 2002). This target load of 11,000 metric tons was first reached in 1981 and has been achieved most years since (Baker et al. 2002). Furthermore, by 1980, agricultural nonpoint sources had replaced point sources as the major contributor of phosphorus to Lake Erie (Dolan et al. 2005).

In the late 1980s, the zebra mussel (*Dreissiena polymorpha*) was introduced into Lake Erie, followed twenty years later by the quagga mussel (*D. bugensis*) (Jarvis et al., 2000). Filtering activities by the dreissenid mussels impact lake food webs and plankton and benthic communities (Jarvis et al. 2000). Mussels have been shown to increase water clarity and alter nutrient cycling (Bierman et al. 2005). Dreissenid mussels help remove plankton and particulate nutrients from the water column by filtering; however, they also increase soluble reactive phosphorus and ammonia levels through excretion (Bierman et al. 2005, Zhang et al. 2006, 2011). In addition, mussels contribute to the proliferation of blue-green algae, including *Microcystis*, by selectively rejecting these types of algae when filtering and provide available nutrients through excretion (Bierman et al. 2005, Vanderploeg et al. 2001, Zhang et al. 2011).

Due to the implementation of various phosphorus control strategies in the late 1970s and early 1980s phosphorus loads were significantly reduced and eutrophic conditions within Lake Erie began to improve throughout the 1980s and early 1990s until the mid-1990s when unexpected eutrophication problems began to reappear. In particular, *Microcystis* blooms began to reoccur in the western basin and continued to occur with varying intensity through present day (National Oceanic and Atmospheric Administration 2009, Ohio Lake Erie Phosphorus Task Force, 2010). A massive bloom in August of 2003 formed and persisted in the western basin for almost a month (National Oceanic and Atmospheric Administration 2009, Ohio Lake Erie Phosphorus Task Force, 2010). Blooms continued to occur from 2004-2006 with extensive blooms also forming in 2007 and 2008 (Joose and Baker 2009, National Oceanic and Atmospheric Administration 2009). The algal bloom that occurred in 2009 spread from the western basin into the central basin (Ohio Lake Erie Phosphorus Task Force, 2010). Stumpf et al. (2012) also reported strong blooms from 2008-2011 with the strongest bloom occurring in 2011. During this time period it has also been reported that shoreline algal problems were more localized and contain a different assemblage of blue-green and green algae than previously reported (Ohio Lake Erie Phosphorus Task Force, 2010). This may indicate different ecological interactions are in play and that phosphorus dynamics may differ from those used in the past.

As the dynamics continue to change within Lake Erie, there are still many trophic relationships and interactions that are greatly unknown. In particular, the detailed relationship between phosphorus loading and *Microcystis* blooms is not fully understood. Stumpf et al. (2012) showed a statistical relationship between spring phosphorus load and the magnitude of the bloom, however, the relationship only held for years after mussels became established suggesting that dreissenids continue to impact the results of the nutrient flows within the system. In order to better understand these and other relationships in the system, the use of models has grown in popularity, particularly in recent years. Models describing eutrophication processes were developed in the 1970s for environmental management practices (Jorgensen, 2010). Models of increased and varied complexity continued to be applied to environmental management decisions into the 1980s and 1990s (Jorgensen, 2010). In more recent years models have been developed that combine hydrodynamic and water quality based processes (Boegman et al., 2008; Jorgensen, 2010). This approach became the trend for recent models in Lake Erie. Boegman et al. (2008) used a two-dimensional hydrodynamic and water-quality reservoir model (CE-QUAL-W2) to address the problem of adequately modeling both physical and biological process in time and space to simulate long term trends. Similarly, Schwab et al. (2009) used a hydrodynamic model of Lake Erie that also included a phosphorus transport model.

Other methods that are being developed for modeling *Microcystis* include statistical modeling and the use of satellite imagery. Millie et al. (2011) used data driven mathematical modeling to evaluate *Microcystis* growth. Stumpf et al. (2012) and Wynne et al. (2010) used satellite imagery and physical data in order to characterize *Microcysitis* blooms within the western basin of Lake Erie.

This project was designed to analyze and compile input data for a hydrodynamic and water quality model (Zhang et al. 2006, 2011), a modified version of Boegman et al.'s 2008 model. The model was developed to look at the relationships between phosphorus loading, *Microcystis* blooms, and dreissenid mussels' impacts, as well as dynamics within the lower food web as a whole. Analysis of input data and model output can provide insight into which drivers and process are affecting the recent massive harmful algal blooms (HABs) in Lake Erie, specifically in relation to increased phosphorus levels throughout the lake.

Model Description

CE-QUAL-W2 was developed by the Army Corp of Engineers to simulate long and narrow water bodies (Cole and Buchak, 1995). It is a two-dimensional, longitudinal and vertical, hydrodynamic and water quality model that has been applied to over 400 water bodies around the world (Cole and Buchak, 1995). The model includes six hydrodynamic variables: free water surface elevation, pressure, horizontal velocity, vertical velocity, constituent concentration, and density; as well as 21 water quality variables: a conservative tracer (such as a dye), suspended solids, coliform, dissolved solids, labile dissolved organic matter (DOM), refractory DOM, algae, labile particulate organic matt (POM), phosphorus, ammonium, nitrate+nitrite, dissolved oxygen, sediment, inorganic carbon, alkalinity, pH, carbon dioxide, bicarbonate, carbonate, iron, and chemical/biological oxygen demand (CBOD) (Zhang, 2006).

This model was configured to Lake Erie by Boegman et al. (2001) to simulate the hydrodynamics of Lake Erie. The lake was divided into 65 vertical layers and 222 longitudinal segments and calibrated to observation for the year 1994.

The model used in this project, EcoLE, modified Boegman et al.'s version by separating the algae into three functional groups; diatoms, non-diatom edible algae (NDEA, and non-diatom inedible algae (NDIA) (Zhang et al. 2001). EcoLE was originally used to simulate the impacts of dreissenid mussels on the lower trophic levels of Lake Erie with input data from 1997, 1998, and 1999 (Zhang, 2006).

The present model incorporates the idea that algal growth is governed by temperature, light, and nutrients using specific equations to properly incorporate resource limitations connected with these factors (Zhang, 2006). In all previous model runs for 1997, 1998, and 1999, Zhang (2006) found no case of nitrogen as the limiting nutrient factor for algal growth. Moving up the food chain, this model focuses on two groups of zooplankton, cladocerans and copepods, which are assumed to consume only edible algae (diatoms and NDEA) and organic particles. Mussels are also included in this model under two processes which include grazing phytoplankton and organic particles, and excreting nutrients. The nutrients submodels were modified from Cole and Buchak (1995) by adding recycling components by crustaceans and dreissenids (Zhang, 2006). Mussels are treated as external forces in the model, thus abundances and size distribution are assumed constant over time. In other words, grazing and nutrient impacts are calculated with a predetermined population density within the lake (Zhang, 2006).

The model takes eight tributaries of Lake Erie into consideration for simulation including rivers and wastewater treatment plants (WWTP). These eight tributaries are the Detroit, Maumee, Sandusky, and Cuyahoga Rivers; the Toledo, Cleveland Westerly, and Cleveland Easterly WWTPs of Ohio; and the Erie WWTP of Pennsylvania. Flows, nutrient concentration, and water temperatures are needed for all tributaries. The model also includes two withdrawals, the Niagara River and the Welland Canal. Meteorological data is also needed for the simulation of the model including wind speed, wind direction, cloud cover, precipitation, and air temperature.

Methods

Data was compiled from various sources to populate the input files to run EcoLE as described above for 2010 (Table 1). Flow, nutrient concentrations, and water temperatures for all eight tributaries, meteorological data, and withdrawal flows were all compiled in order to create input files to run EcoLE. Due to some computer difficulties and time restraints I was not able to complete simulation runs using the 2010 data. As a result input data from 1998 and 2010 were compared to look at any difference and determine likely model outcomes for the 2010 season.

All 2010 input data was collected in a similar fashion to the data in 1998. Many of the same sources were used adding to the consistency of the data. In order to allow for direct comparison of 1998 and 2010 data, computations were applied to annual phosphorus loads and algal biomass. Loads, in metric tons, were calculated using the formula posted by Heidelburg College:

time x by volume/time x amount/volume x 0.0024468 (a conversion factor)

2010 algal biomass was calculated by converting the chlorophyll *a* in micrograms per liter to biomass in milligrams per liter. This conversion first converts chlorophyll *a* values to milligrams per liter by dividing by 1000 and then multiplies by a conversion factor of 100.

Input data from 1998 and 2010 were compared using simple graphs. Since output data from the model was available for 1998 for the in lake concentrations and field data was available for the western basin for 2010, water quality variables were compared to look for changes in spatial patterns of magnitude between decades.

Data

Because the model was not run with the 2010 data, data analysis focused on examining differences between the input data from 1998 and 2010. Figure 1 shows the model segments for the western basic along with the discrete points sampled for the 2010 in lake concentrations. Original data in the proper format for the model input files can be found as an attachment to this paper.

Figure 3 shows the average daily inflow rate in cubic feet per second from each of the rivers used to calculate loads for the model for both years. The Detroit River was the largest water input making up 93% of the inflow in 1998 and 87% in 2010. The Maumee River was the second largest source contribution for both years. WWTP flow rates decreased from 3.35% to 0.16% of the river inflow between 1998 and 2010 (Figure 4) mostly because of the increase in river discharge observed in 2010. Table 2 gives a list of the yearly phosphorus loads in metric tons for all inputs, rivers and WWTPs, for both years. Loads increased for all WWTPs and increased in the Detroit River and Maumee River. In contrast, loads decreased slightly for the Sandusky and Cuyahoga Rivers in 2010 compared to 1998.

Constituent river concentrations were averaged to a monthly value in order to plot 1998 and 2010 together and analyze yearly trends. Despite continued emphasis on phosphorus control measures in the entire basin, 2010 phosphate values were generally higher throughout the year for all four rivers (Figure 5). Trends in ammonium concentrations were basically the same for all rivers, with the Detroit River having nearly identical monthly averages (Figure 6). Detroit River concentrations for nutrients were mathematically derived data and not actually sampled, thus they were expected to have similar trends in both years. Nitrate values also generally exhibited similar monthly trends across the decades, but with some peaks occurring in different months (Figure 7). Concentrations of suspended solids were generally the same or lower for 2010 compared to 1998 (Figure 8). Despite its greater flow the Detroit River suspended solids concentrations were roughly ten percent that of the other rivers. Average monthly temperatures were exactly the same between the two years in the Maumee (Figure 9a) and Cuyahoga (Figure 9b). The Sandusky (Figure 9c) had nearly the same temperatures except for a spike in February of 2010 that did not occur in 1998. The Detroit River (Figure 9d) also had very similar temperatures between the two comparison years.

Constituent values for the WWTP were graphed similarly. Total phosphorus concentrations were slightly higher in 2010 than 1998 for all four WWTPs (Figure 10). The ammonium values (Figure 11) were generally lower in 2010 with the Cleveland Westerly WWTP in 2010 than 1998. The Erie WWTP ammonium and nitrate values were not graphed because they were unavailable for both years. The nitrate values were higher in 2010 than 1998 (Figure 12). The suspended solids were generally the same (Figure 13). The suspended solids values were slightly higher in 2010 for the Erie and Cleveland Easterly WWTPs. The suspended solids values were slightly lower in 2010 for the Toledo WWTP. Temperatures were generally the same to slightly higher for 2010 for all WWTPs (Figure 14).

To examine trends in within lake nutrient concentrations, monthly averages were plotted for 2010 across the western basin of Lake Erie by model segment throughout the growing/sampling season along with the 1998 model output in lake data as a comparison. Because the 1998 data was from the model output, the result was smooth lines over the segments of the western basin. 2010 data were discrete sampling points within certain segments of the model; see Figure 1 for station locations within the corresponding model segments. The soluble reactive phosphorus was quite a bit higher in the 2010 than the 1998 model predictions (Figure 15). The 2010 numbers vary more than that of the 1998 model predictions. The soluble reactive phosphorus for 2010 was highest in June across the western basin. There was typically a peak in segments five and seven with a dip in value at segment 6. There was also a large decrease in values across the western basin in September. Ammonium was typically lower for the 2010 season than for 1998, except for October (Figure 16). The ammonium was highest in October and lowest in August with the trend being pretty consistent across the basin. The trend in 2010 was for the values to decrease as you move eastward into the lake, but in 1998 values tend to spike in the east most segment. The nitrate values decreased from west to east for both years (Figure 17). The nitrate values were highest in June and continue to decrease by a factor of ten by September and October.

Algal biomass values were similar from west to east for both years (Figure 18). The algal biomass levels were lower in June and July and increase in August with the largest spike in September. The algal biomass levels were much larger for 2010. Algal biomass for 1998 includes a sum of all NDIA, NDEA, and diatoms from the model output.

Note that phosphate is reported as soluble reactive phosphorus. Also, due to data availability and model parameters, total phosphorus is used for WWTPs and phosphate is used for rivers.

Discussion

According to the data, there was an increased amount of phosphorus going into Lake Erie in 2010 than there was in 1998. Increased river and WWTP inputs of phosphate and total phosphorus values also resulted in increased phosphorus concentrations within the lake. Zhang (2006) found that phosphorus was always the limiting nutrient for non-diatom algae during 1997, 1998, and 1999. Stumpf et al. (2012) also found corresponding increases in *Microcystis* blooms with increased spring phosphorus loads. Taking this into consideration it is expected that there should have been more phytoplankton production within the system during 2010, which appeared to be confirmed by a relatively strong *Microcystis* bloom during this year.

Nitrogen values were roughly the same for both years for all tributaries. However, because phosphorus is thought to be the limiting nutrient, this should not have any major effect on productivity. However, this may result in lower nitrogen to phosphorus ratios, which may favor nitrogen fixing algae.

Temperature was also basically constant between the two years. Given the similarities between all eight tributaries both years, except for the slightly increased phosphorus levels, it can be assumed that either phosphorus plays a big role in *Microcystis* formation and proliferation, there are other outside contributors, or there is something happening in the lake. Given the work done by Stumpf et al. (2012), who found statistically significant relationships between increased spring phosphorus load and strong *Microcystis* blooms, this assumption is firmly supported.

According to 2010 mussel density reports (Catherine Riseng, personal communication) and mussel densities reported by Jarvis et al. (2000) for the 1998 season, there has only been a minor decrease of Dreissenid density from 1998 to 2010, from 3712 per square meter to 3361 per square meter. While the lack of change in mussel densities would indicate that mussels are not a major factor in explaining differences in water quality changes between 1998 and 2010, it has been concluded that mussels are clearly important in mediating the algal bloom response to phosphorus loading (Stumpf et al. 2012).

Input concentrations from the WWTPs were very similar between the two years, expect for the nitrate concentrations. There was an obvious increase in the nitrate concentrations of 2010 compared to that of 1998. There is no definitive reason available for these increases at this time.

In lake data for 2010 seem to have values similar to those that would be expected. However, more data points and values from across the lake may give a better picture of the lake as a whole. The spike in algal biomass levels in August and September may correlate with *Microcystis* blooms during the same period. Values between 1998 model output and 2010 data samples show a tenfold increase for parts of the sampling season. Data collected by the EPA in August of 1998 further in lake, just east of where the graphs pictured here end, found an average algal biomass of 0.239 milligrams per liter. This value is comparable to the model output moving eastward into the lake. Therefore, the algal biomass increases pictured seem consistent with actual data collection.

Chaffin et al., (2011) found that *Microcystis* was most abundant in the transition zone between the western shore and offshore zones in Western Lake Erie. Data represented in this paper does not cover this transitional zone, but running the model with the 2010 data would cover this zone and may show the same simulation.

Several studies; Chaffin et al. (2011), Rinta-Kanto et al. (2009), Saxton et al. (2012), Schwab et al. (2009), Stumpf et al.(2012); have indicated that phosphorus is the most important factor regulating *Microcystis* production. Millie et al. (2009) and Davis et al. (2009) suggest that when nutrients are sufficient, seasonal variations in light and temperature become the primary factors regulating *Microcystis* growth. Boegman et al. (2008) suggest that wind-induced mixing and weak stratification contribute to blooms by regulating the supply of plankton, including blue-green algae, to mussel beds.

The model analyzed in this study was originally created to look at mussel impacts on water quality. In relation to use for *Microcystis* there may be slight inconsistencies in predictive capabilities. However, given the input data patterns and the current literature, this model should provide some insight for future *Microcystis* blooms specifically in the western basin of Lake Erie.

Conclusion

Given the related research and data compilation, working to get the model running with the 2010 data may prove to inform some of the *Microcystis* bloom interactions that have recently occurred. Further information about phosphorus concentrations within the lake could also correlate to the spike in bloom events. There have been some changes in all three factors being examined, phosphorus levels, *Microcystis*, and dreissenids. Given recent work by Stumpf et al. (2012) spring phosphorus load is significantly important to the strength of the Microcystis bloom. However, the exact timing and mechanisms of this stimulus is unclear. Continued future studies should be performed to further develop and determine interacting relationships between hydrologic loads, hydrodynamics, and food web process, to help this model better forecast changes in concentration, distribution, and size.

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Tables and Figures

Location	Data	Source
Lake Erie	meteorological	http://www.ncdc.noaa.gov
Maumee River	flow, nutrient concentration, water temperature	Heidelberg College Tributary Data Download
Sandusky River	flow, nutrient concentration, water temperature	Heidelberg College Tributary Data Download
Cuyahoga River	flow, nutrient concentration, water temperature	Heidelberg College Tributary Data Download
Detroit River	flow, nutrient concentration, water temperature	Dave Dolan UW-Green Bay
Toledo WWTP	flow, nutrient concentration, water temperature	Chris Bowman Ohio EPA
Cleveland Westerly WWTP	flow, nutrient concentration, water temperature	Chris Bowman Ohio EPA
Cleveland Easterly WWTP	flow, nutrient concentration, water temperature	Chris Bowman Ohio EPA
Erie WWTP	flow, nutrient concentration, water temperature	Chris Bowman Ohio EPA
Niagara River	flow	USGS
Western Lake Erie	in lake nutrient concentration and water temperature	GLERL OHH project

Table 1: Data sources for EcoLE input data

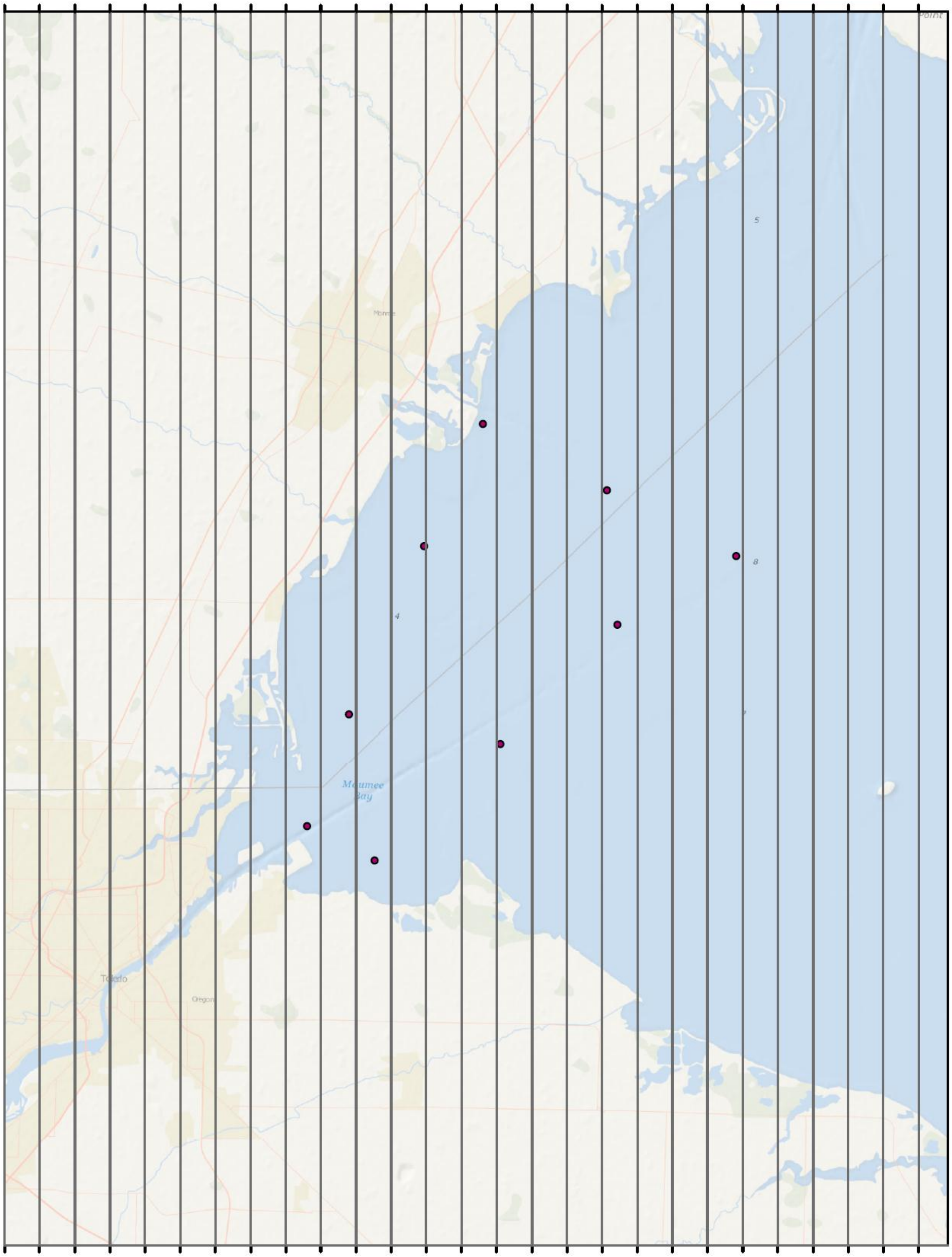


Figure 1: A map of the western basin of Lake split into the model segments with the points representing the sampling site for the 2010 in lake data.

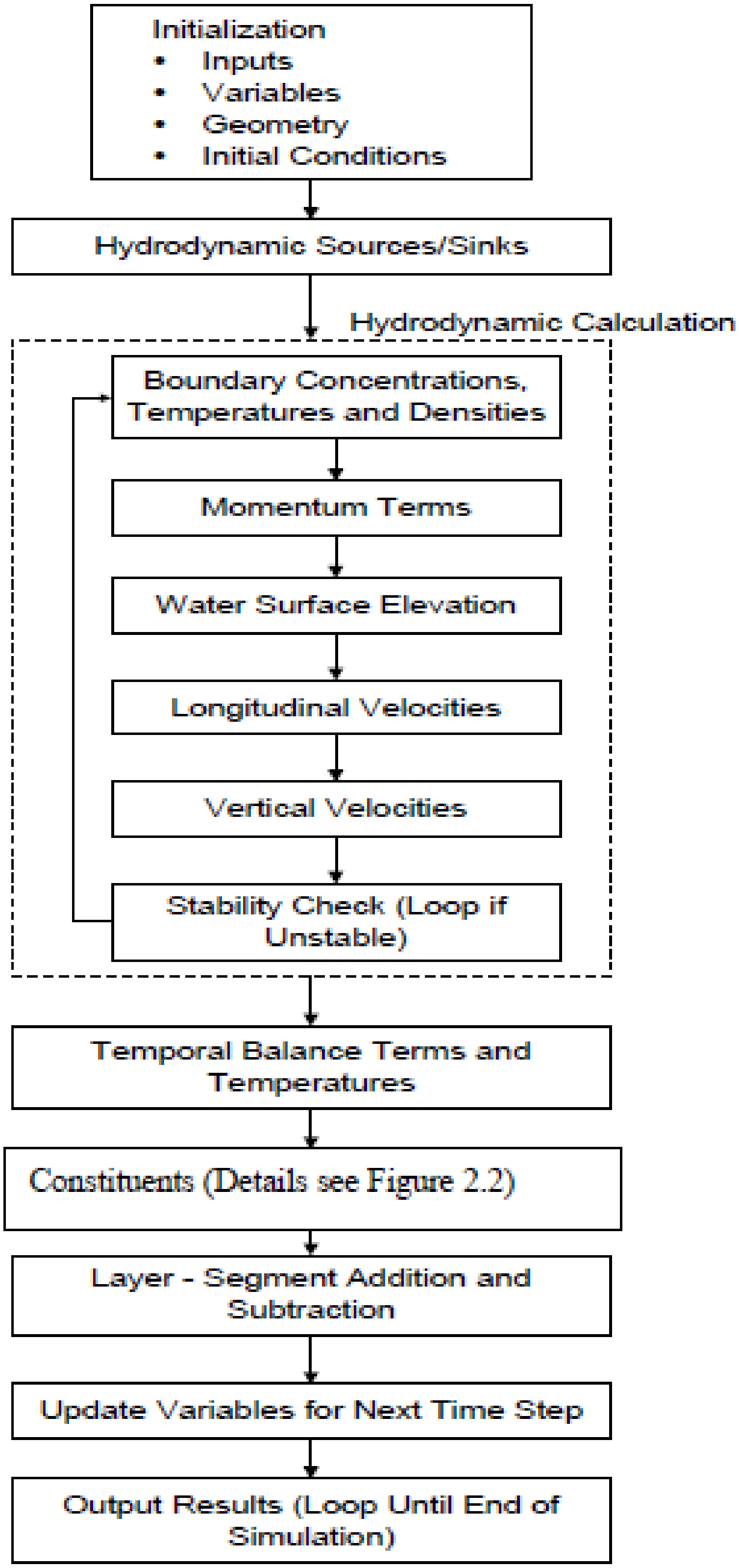


Figure 2: Flowchart of the model, EcoLE (from Boegman et al. 1999 and Zhang 2006)

Yearly Phosphors Loads in Metric Tons		
	1998	**2010**
Detroit River	458	623
Maumee River	1428	2674
Sandusky River	458	385
Cuyahoga River	217	165
Toledo WWTP	2	10
Cleveland Easterly WWTP	1	12
Cleveland Westerly WWTP	3	11
Erie WWTP	3	17

Table 2: Yearly phosphorus loads in metric tons for each input in both years

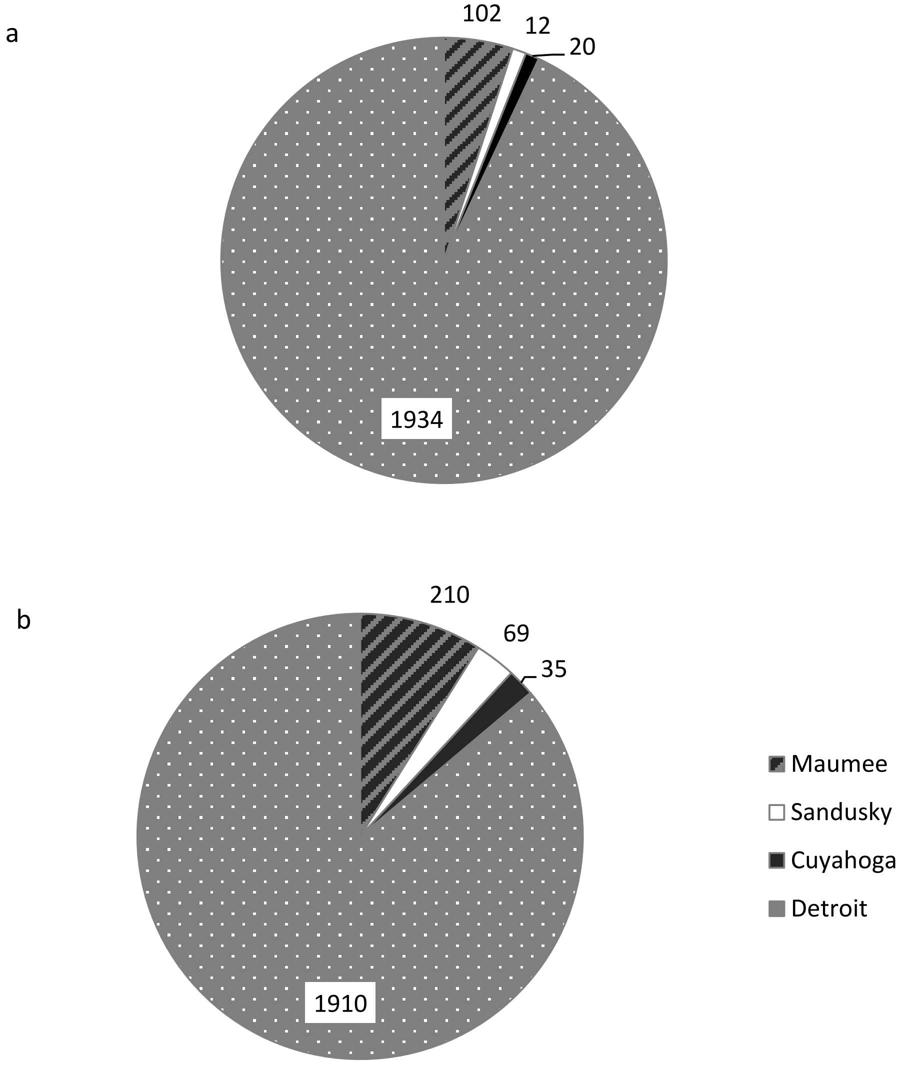


Figure 3: Average daily discharge rate (CFS) for each river in 1998 (a) and 2010 (b)

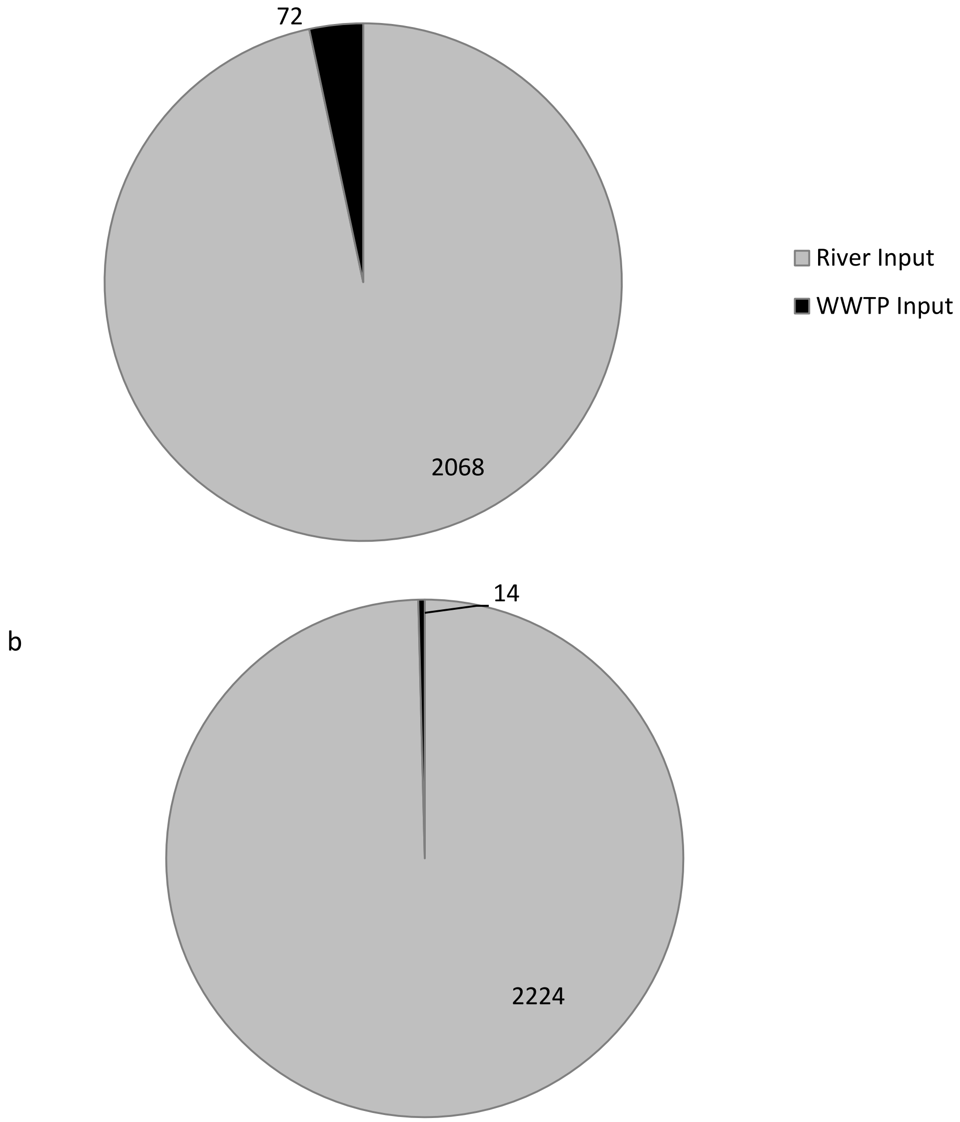


Figure 4: Average daily discharge (CFS) of the river input contribution and the WWTP input to Lake Erie in 1998 (a) and 2010 (b)

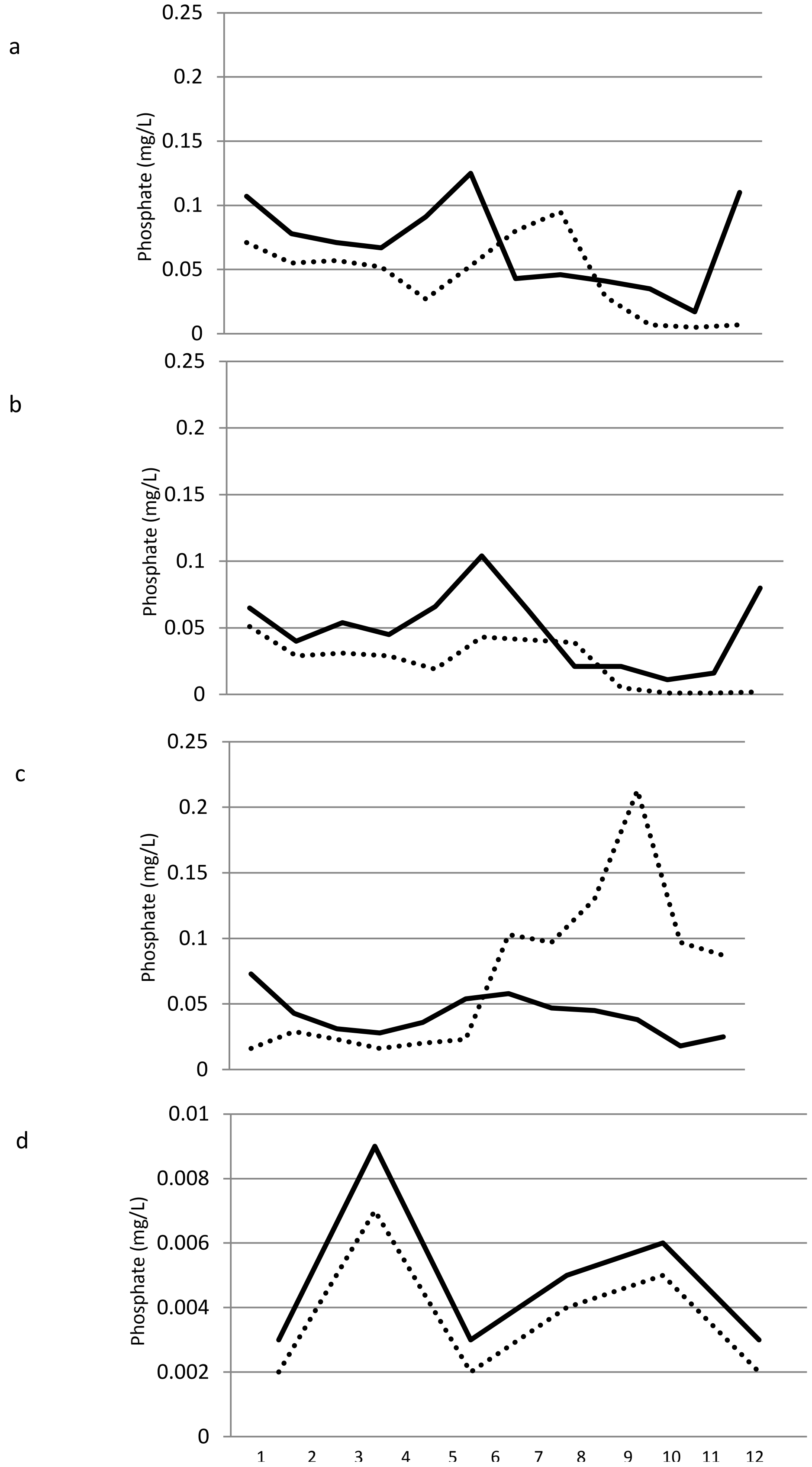


Figure 5: River phosphate is graphed on the x-axis in mg/L over a year time period by month with 1998 (dashed line) and 2010 (solid line) for the Maumee River (a), Sandusky River (b), Cuyahoga River (c), and Detroit River (d). Note the difference in scale of the phosphate levels for the Detroit River.

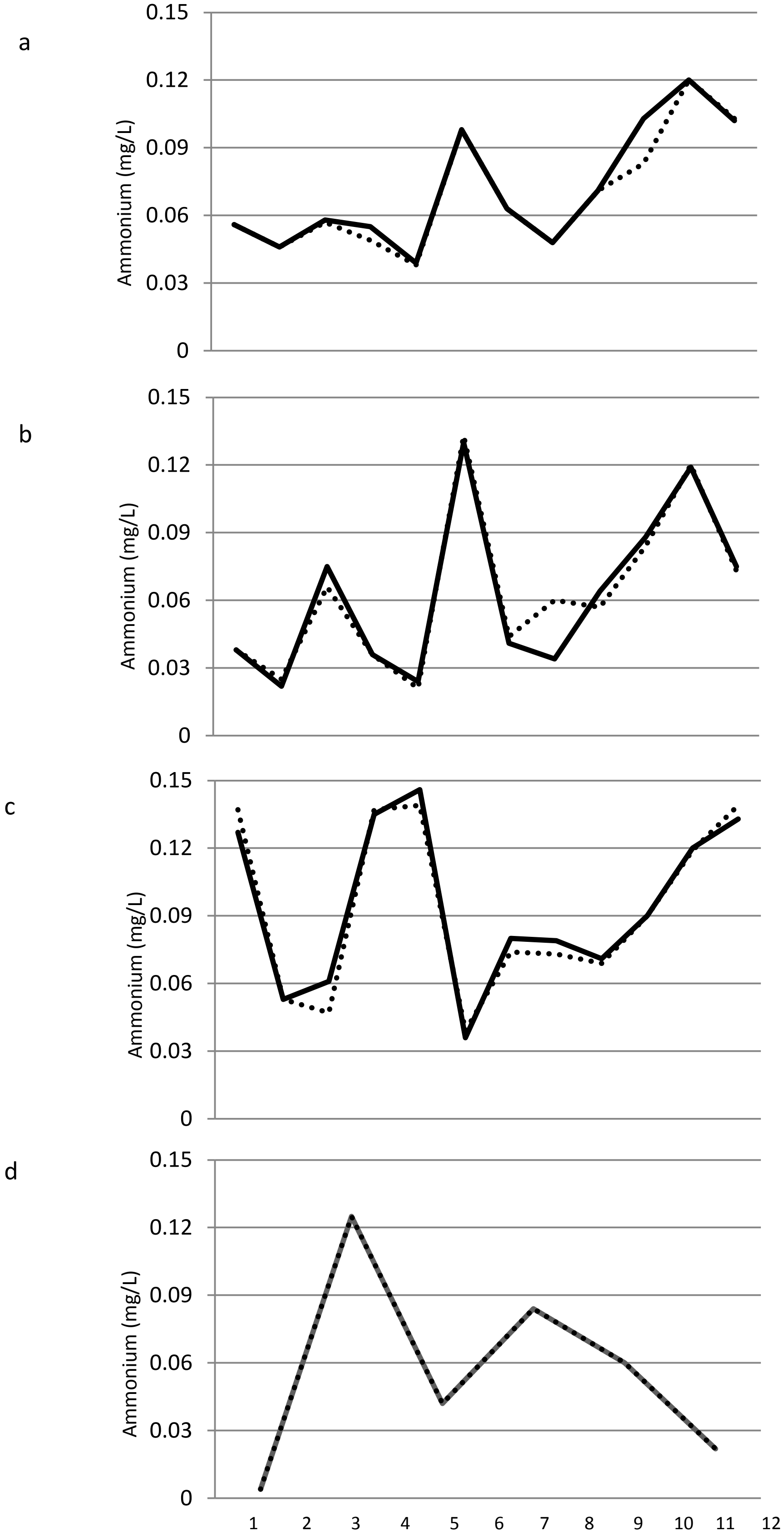


Figure 6: River ammonium is graphed on the x-axis in mg/L over a year time period by month with 1998 (dashed line) and 2010 (solid line) for the Maumee River (a), Sandusky River (b), Cuyahoga River (c), and Detroit River (d).

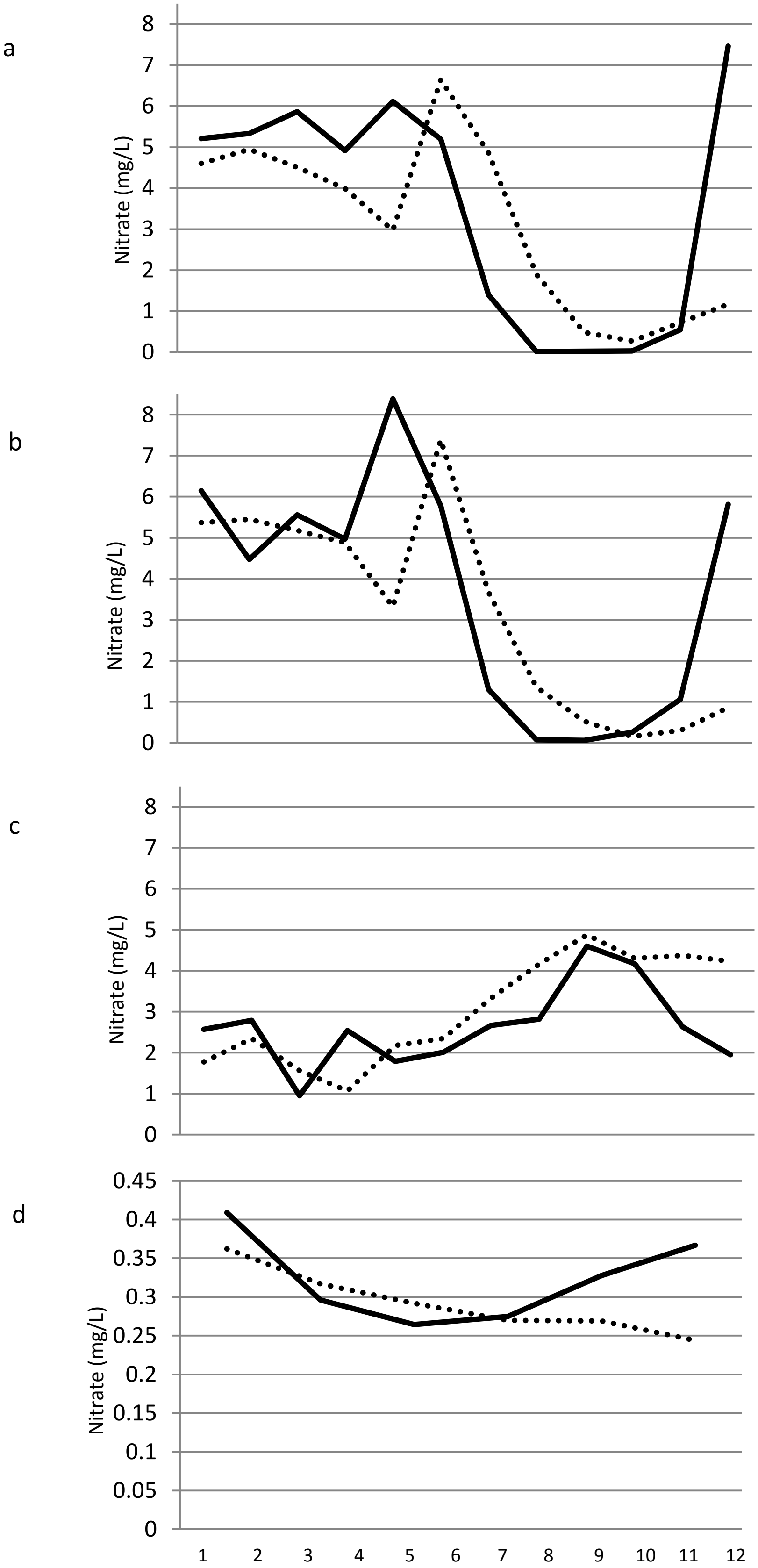


Figure 7: River nitrate is graphed on the x-axis in mg/L over a year time period by month with 1998 (dashed line) and 2010 (solid line) for the Maumee River (a), Sandusky River (b), Cuyahoga River (c), and Detroit River (d). Note the difference in scale of the nitrate levels for the Detroit River.

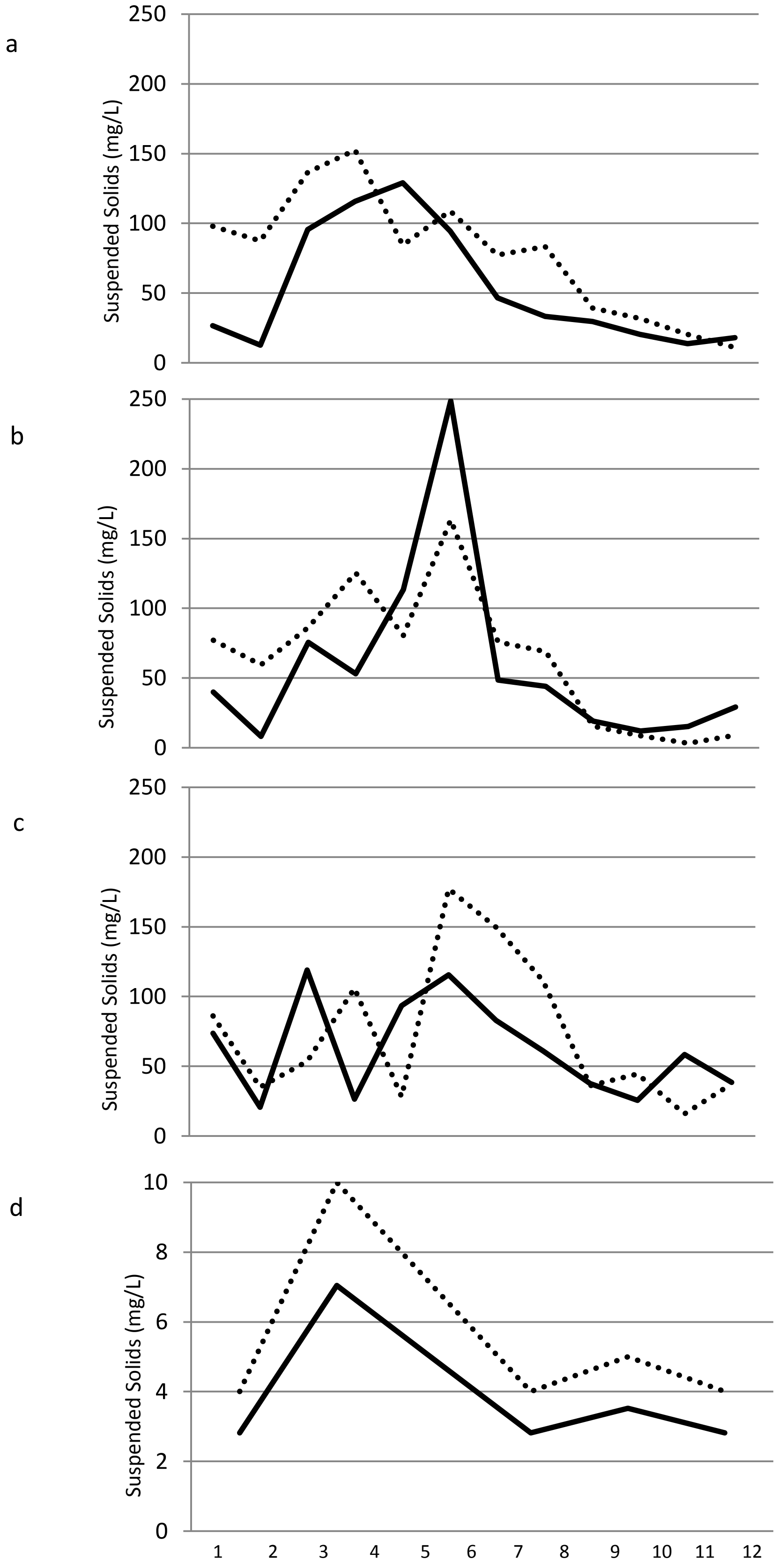


Figure 8: River suspended solids is graphed on the x-axis in mg/L over a year time period by month with 1998 (dashed line) and 2010 (solid line) for the Maumee River (a), Sandusky River (b), Cuyahoga River (c), and Detroit River (d). Note the difference in scale of the suspended solids levels for the Detroit River.

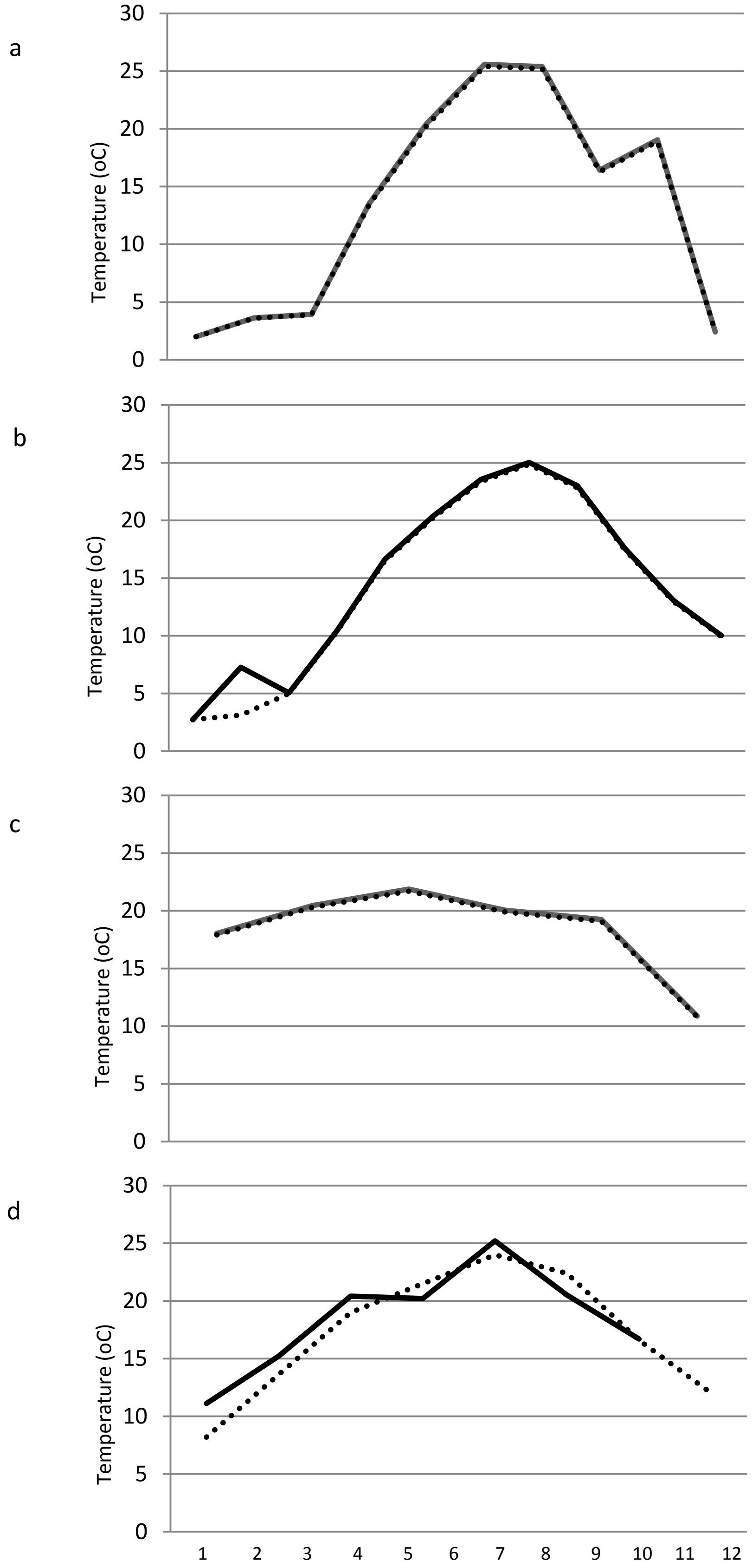


Figure 9: River temperature is graphed on the x-axis in degrees Celsius over a year time period by month with 1998 (dashed line) and 2010 (solid line) for the Maumee River (a), Sandusky River (b), Cuyahoga River (c), and Detroit River (d).

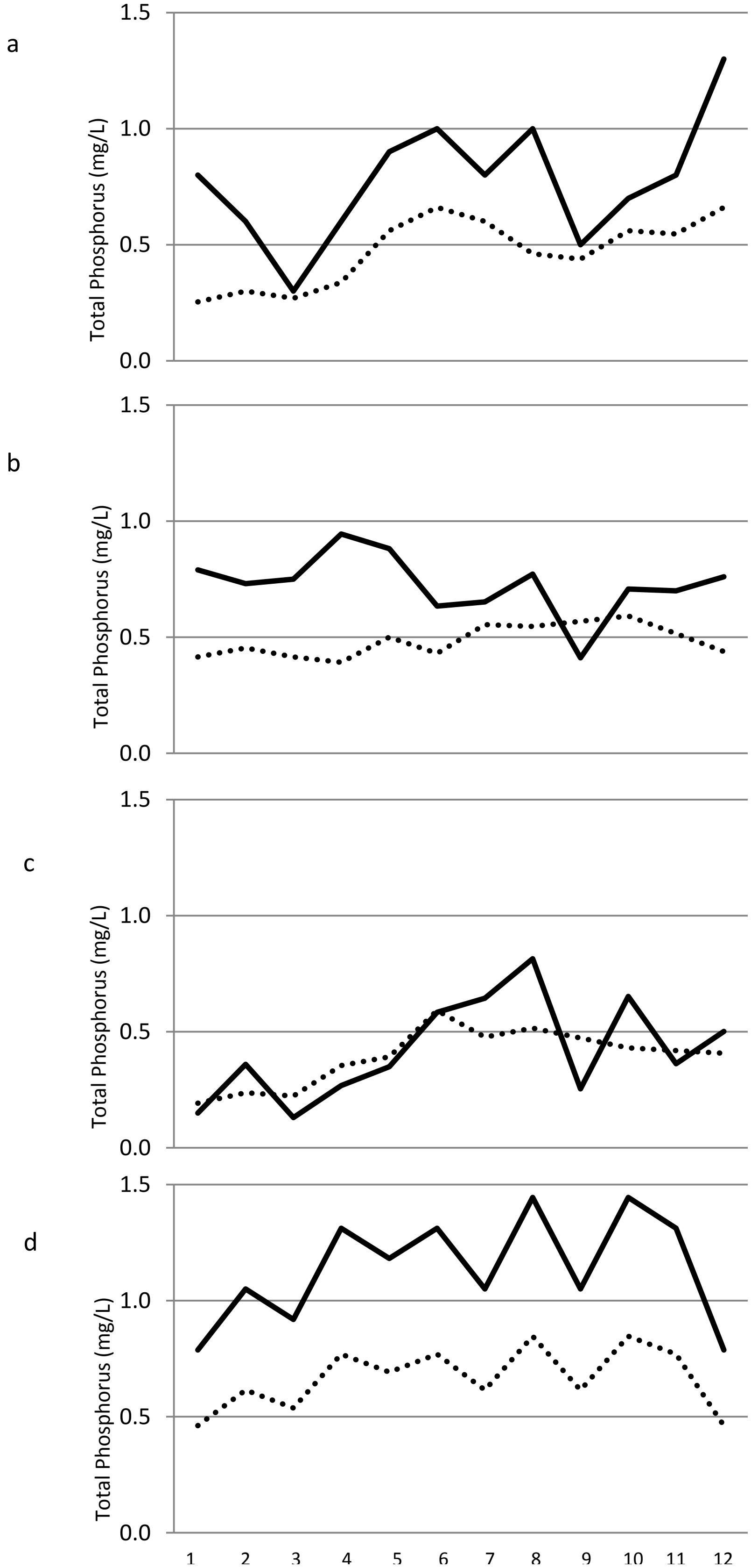


Figure 10: WWTP total phosphorus is graphed on the x-axis in mg/L over a year period by month with 1998 (dashed line) and 2010 (solid line) for the Toledo WWTP (a), Cleveland Westerly WWTP (b), Cleveland Easterly WWTP (c), and Erie WWTP (d).

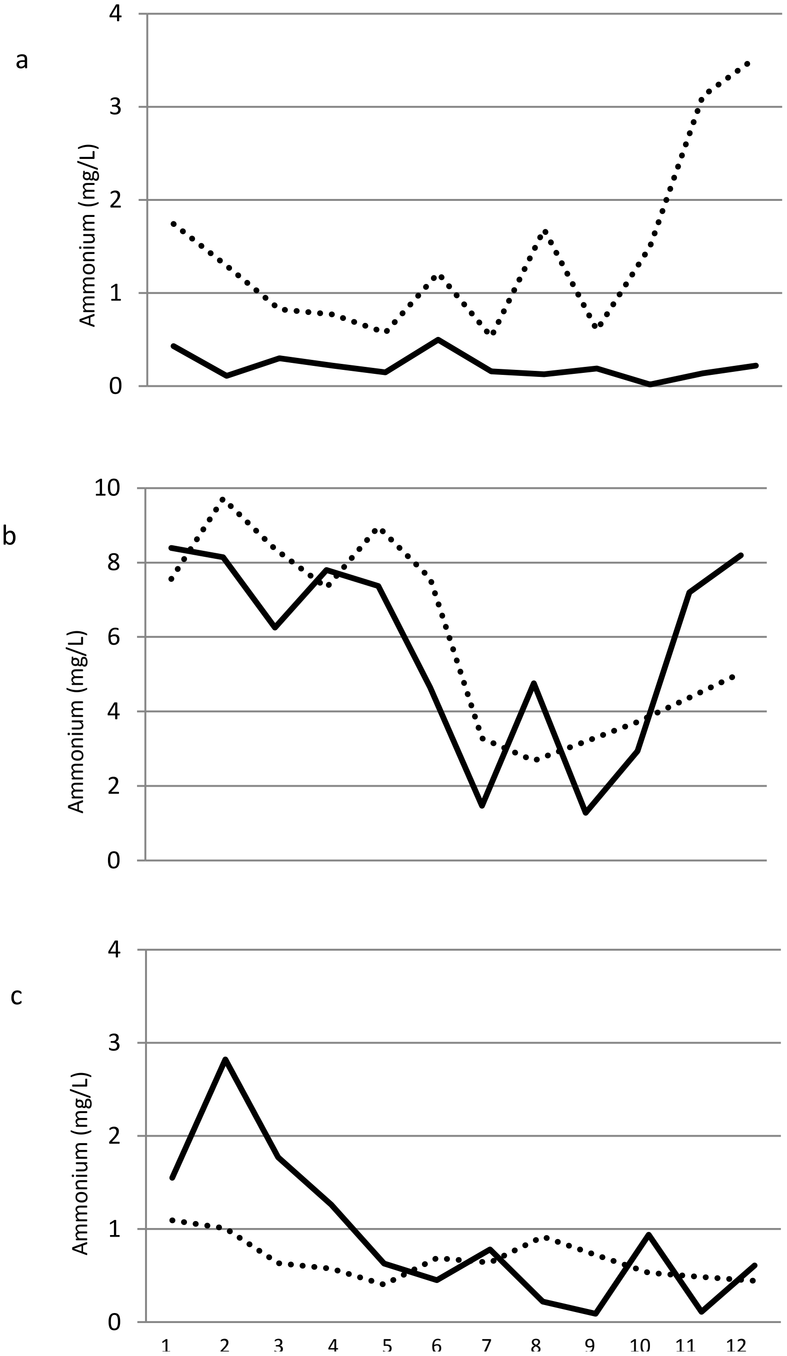


Figure 11: WWTP ammonium is graphed on the x-axis in mg/L over a year period by month with 1998 (dashed line) and 2010 (solid line) for the Toledo WWTP (a), Cleveland Westerly WWTP (b), and Cleveland Easterly WWTP (c). Note the difference in scale for the Cleveland Westerly plant. The Erie WWTP is not shown because data was unavailable.

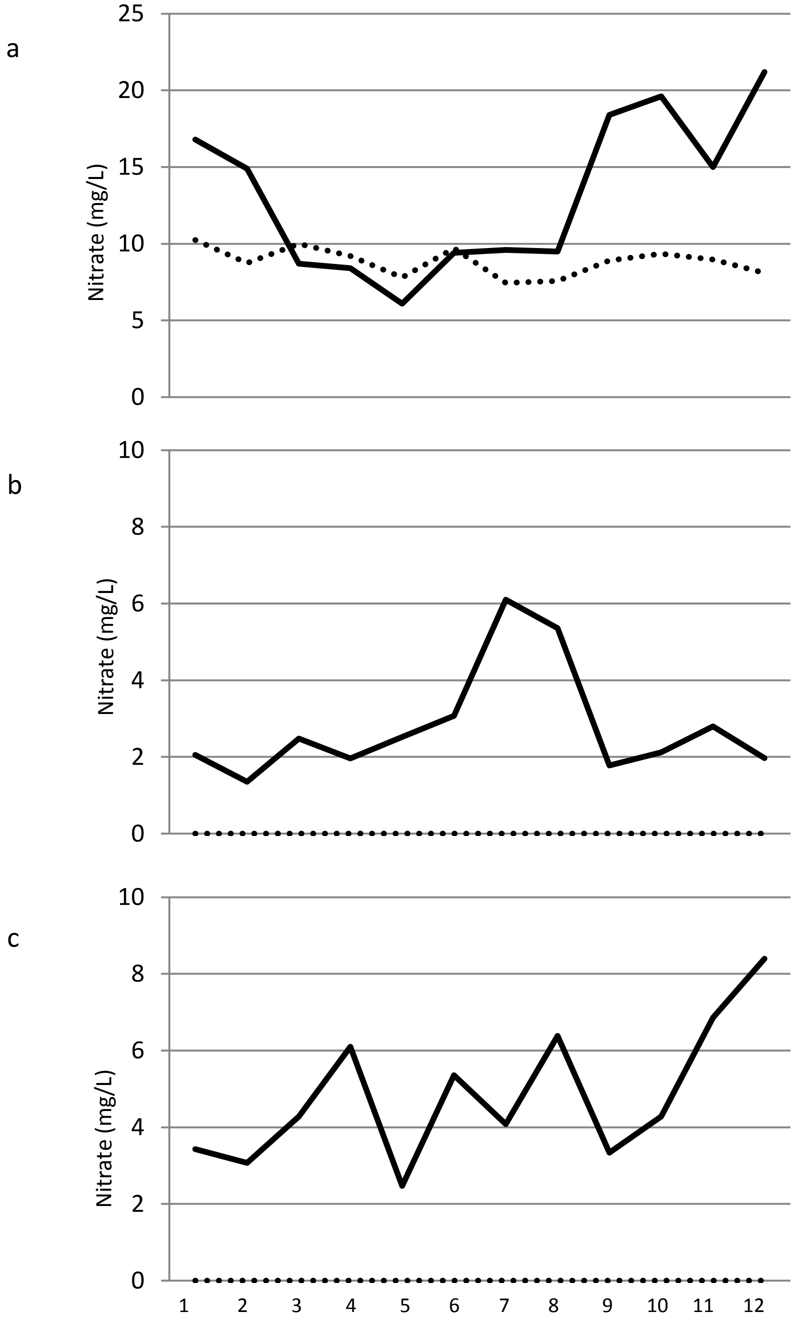


Figure 12: WWTP nitrate is graphed on the x-axis in mg/L over a year period by month with 1998 (dashed line) and 2010 (solid line) for the Toledo WWTP (a), Cleveland Westerly WWTP (b), and Cleveland Easterly WWTP (c). Note the difference in scale for the Toledo plant. The Erie WWTP is not shown because data was unavailable.

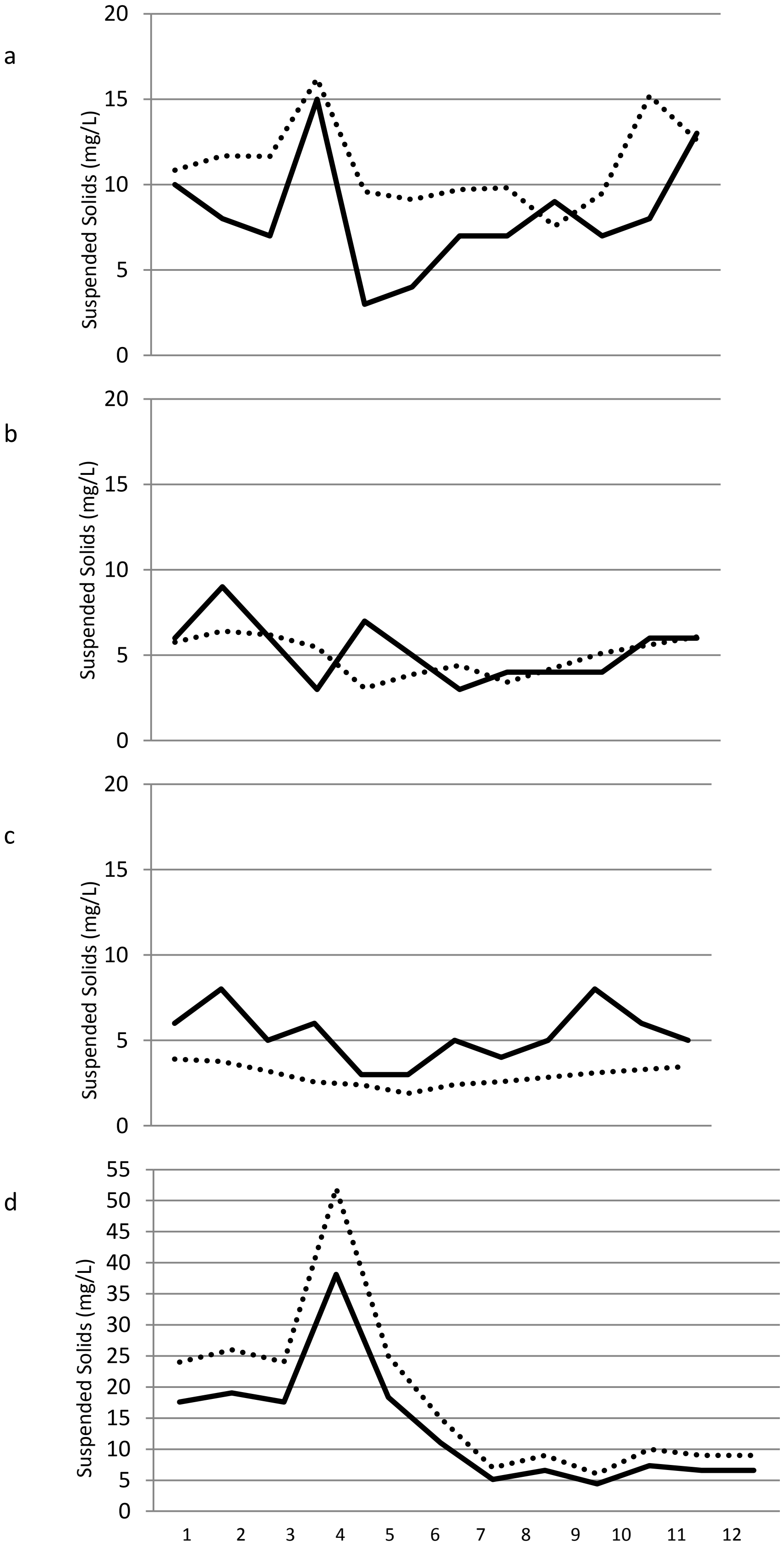


Figure 13: WWTP suspended solids is graphed on the x-axis in mg/L over a year period by month with 1998 (dashed line) and 2010 (solid line) for the Toledo WWTP (a), Cleveland Westerly WWTP (b), Cleveland Easterly WWTP (c), and Erie WWTP (d). Note the difference in scale for the Erie plant.

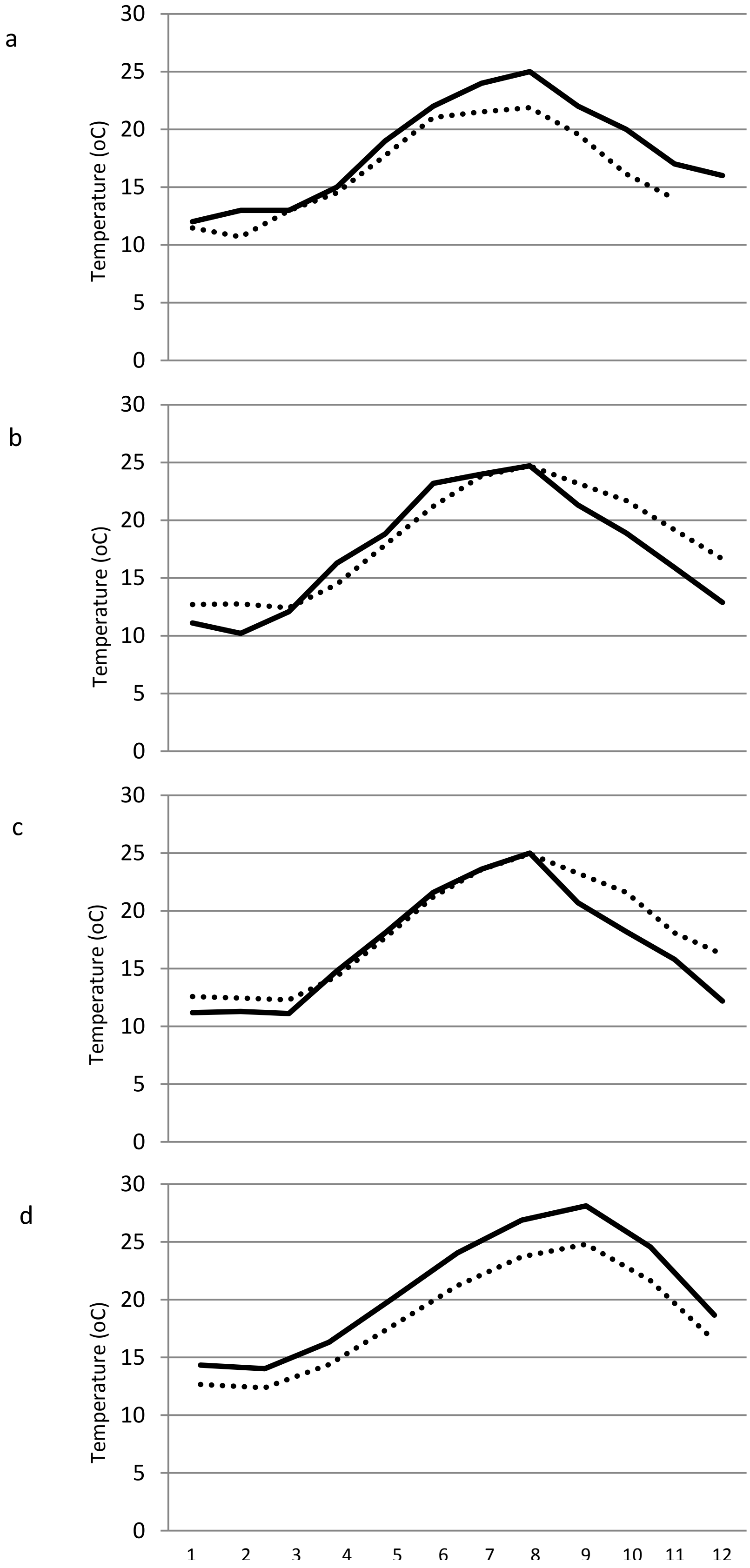
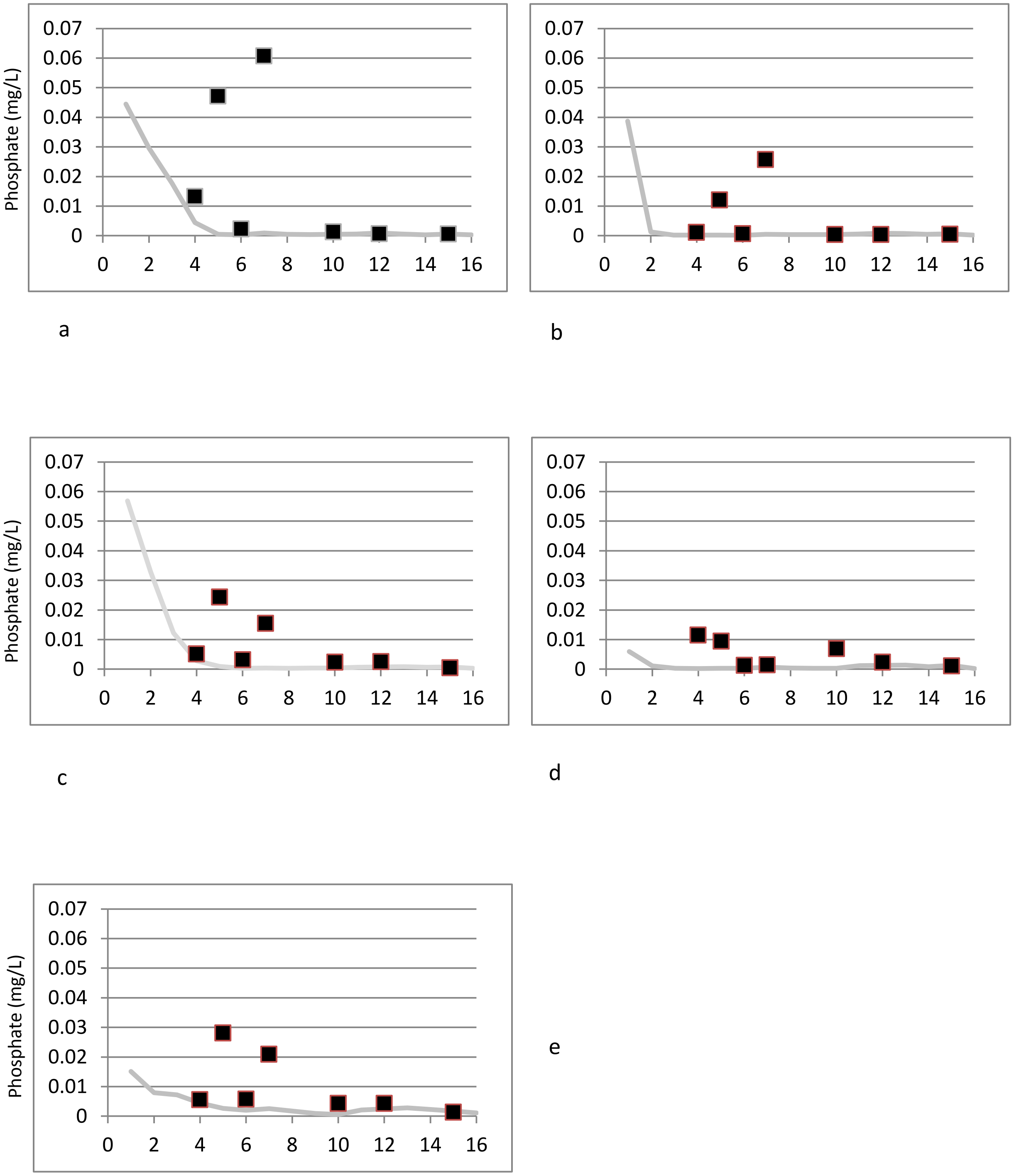


Figure 14: WWTP temperature is graphed on the x-axis in degrees Celsius over a year period by month with 1998 (dashed line) and 2010 (solid line) for the Toledo WWTP (a), Cleveland Westerly WWTP (b), Cleveland Easterly WWTP (c), and Erie WWTP (d).



a

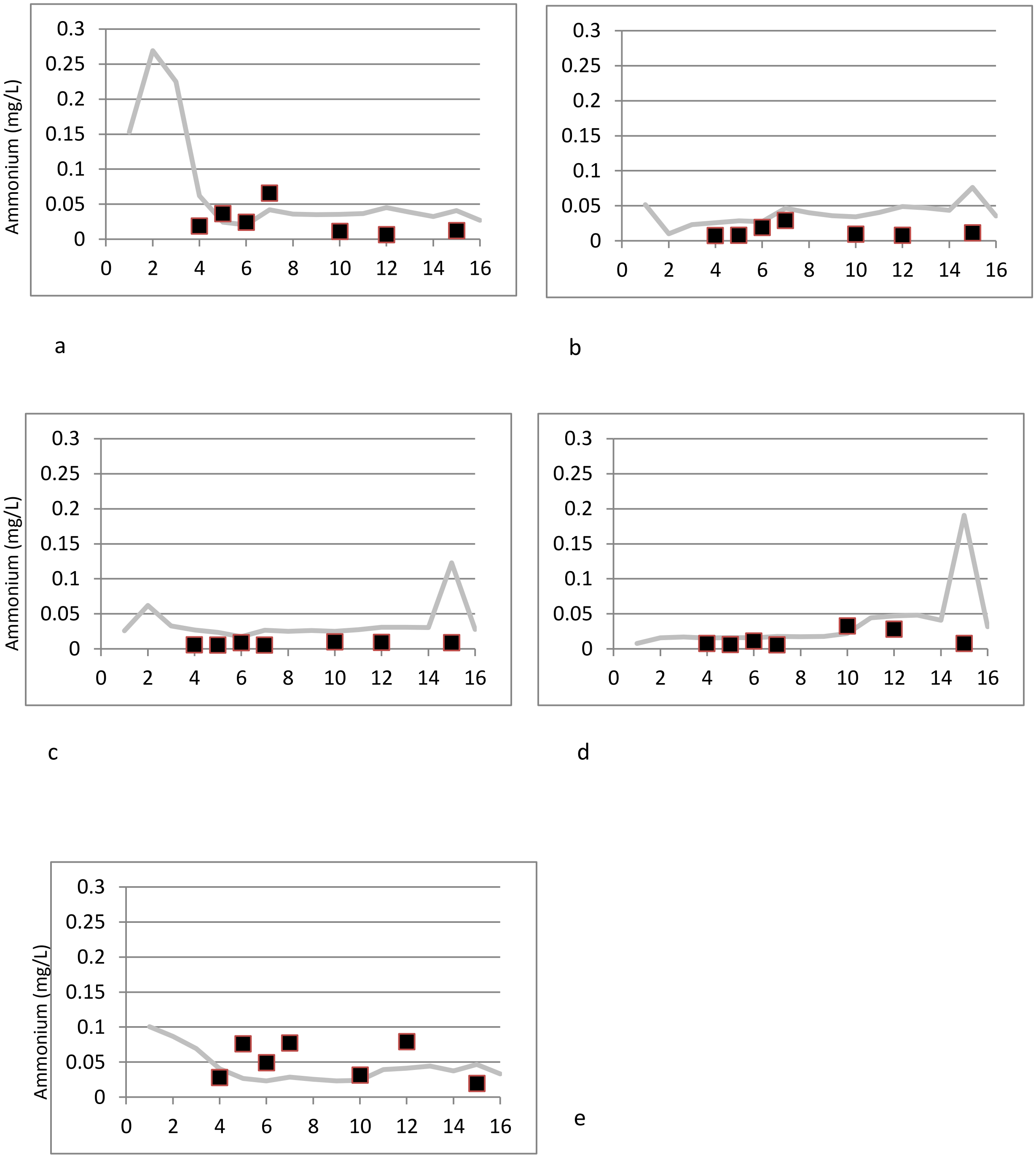
b

c

d

e

Figure 15: In-lake phosphate values in mg/L are plotted over the model segments of the western basin. 1998 data is a smooth line because it is the model output. 2010 data are plotted as discrete sample point in specific segments. (a) represents June (b) is July (c) is August (d) is September and (e) is October



a

b

c

d

e

Figure 16: In-lake ammonium values in mg/L are plotted over the model segments of the western basin. 1998 data is a smooth line because it is the model output. 2010 data are plotted as discrete sample point in specific segments. (a) represents June (b) is July (c) is August (d) is September and (e) is October

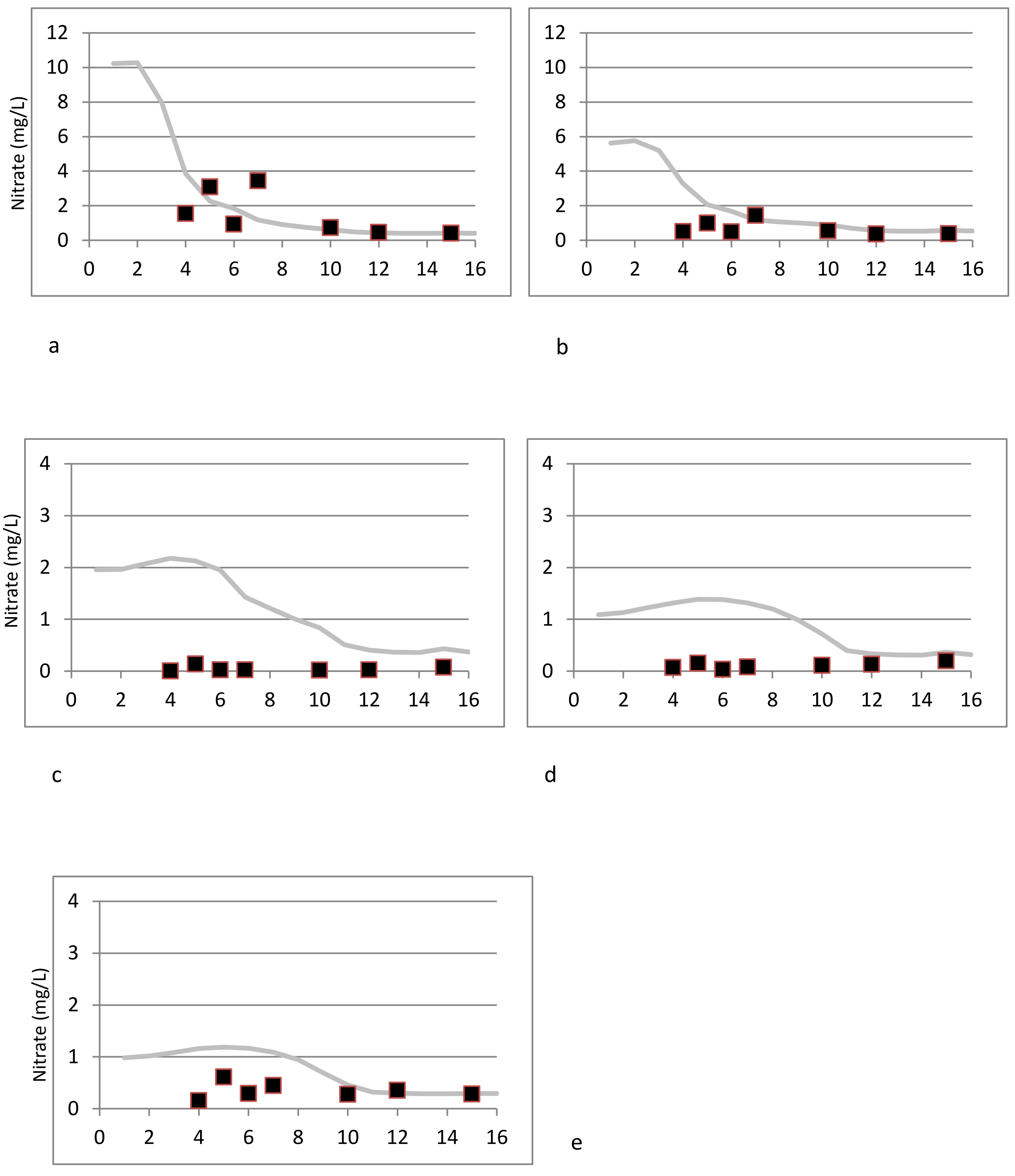


Figure 17: In-lake nitrate values in mg/L are plotted over the model segments of the western basin. 1998 data is a smooth line because it is the model output. 2010 data are plotted as discrete sample point in specific segments. (a) represents June (b) is July (c) is August (d) is September and (e) is October

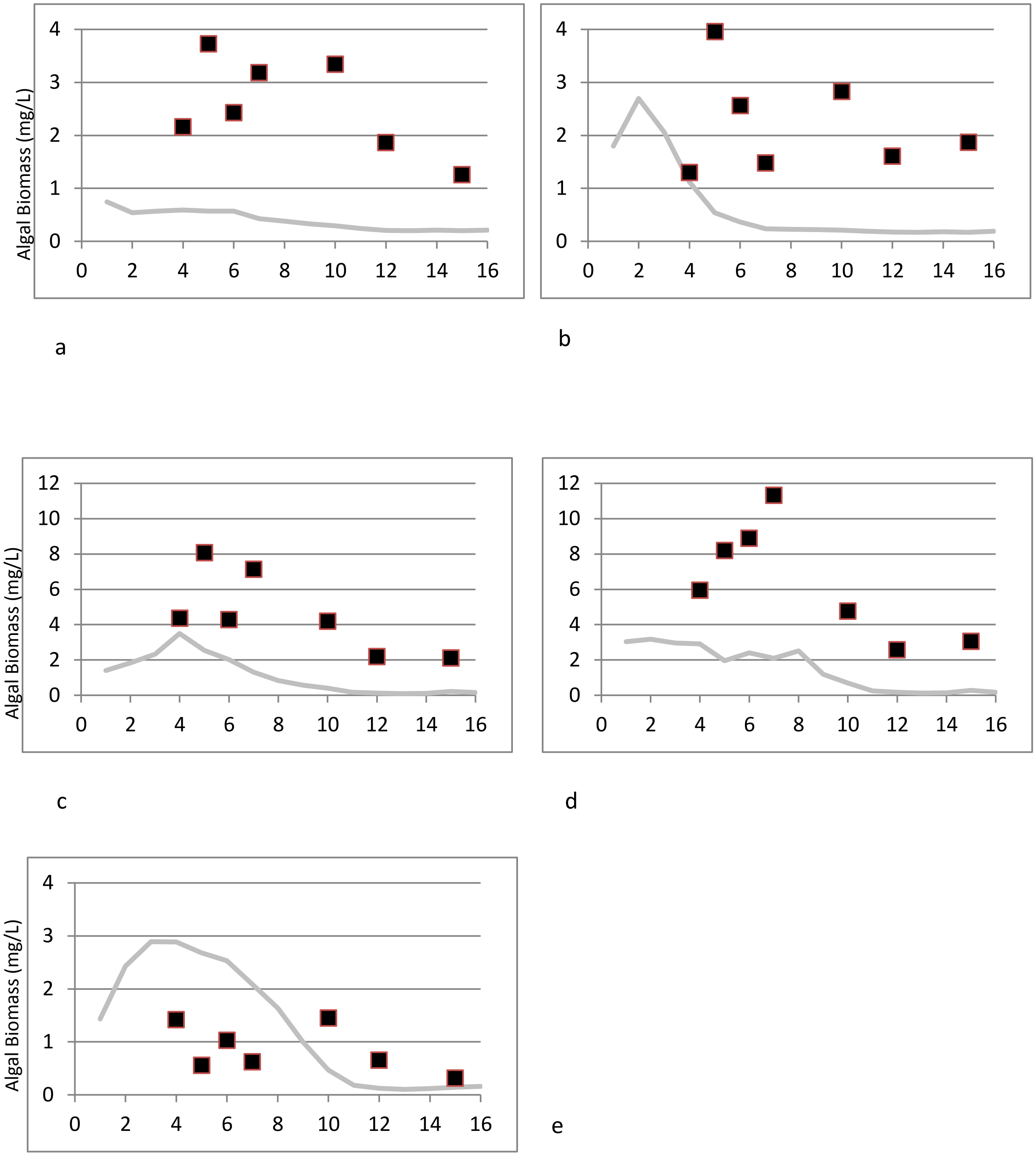


Figure 18: In-lake algal biomass values in mg/L wet weight are plotted over the model segments of the western basin. 1998 data is a smooth line because it is the model output. 2010 data are plotted as discrete sample point in specific segments. (a) represents June (b) is July (c) is August (d) is September and (e) is October