

**ARTIFICIAL BASIN MORPHOMETRY AS A FACTOR IN OXYGEN STRATIFICATION IN
PONDS AND RESERVOIRS OF SOUTHWEST FLORIDA**

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INTRODUCTION

Artificial ponds or reservoirs represent a conspicuous element of the landscape in southwest Florida. The number of artificial basins in this region has increased dramatically over the last 30 years and in some catchments, represent more than half the total area. Coastal south Florida has relatively low relief with about one foot elevation increase per mile from the coast inland. The low relief creates the need for elevating developed areas to avoid flooding and results in the excavation of artificial ponds or lakes for fill.

Typically basins excavated for fill also serve as stormwater treatment basins and other uses including irrigation. These artificially excavated basins are designed to meet stormwater runoff volumes related to impervious area associated with some type of development, typically residential. The area and volume of the basin is regulated through a permitting process designed to meet specific storm event standards for treating stormwater. Stormwater is typically managed to reduce the effects of nutrients and total suspended solids on receiving waters. The duration of treatment or “residency time” is partially regulated by a water control structure (outfall) with a control elevation that regulates the rate of flow and residency time through the basin. Typically a minimum residency time (e.g. 14 days) is necessary to meet the stormwater pollutant reduction targets assumed for wet detention systems.

Artificial reservoirs also result from mining operations typically in this region for sand and gravel. Mining operations generally result in relatively deep basins with low surface to volume ratios. In some situations, residential communities, including waterfront properties are developed in association with mine reservoirs that are no longer in operation.

Through time, artificial ponds or reservoirs associated with some type of development result in problems related to water quality or over-enrichment typically manifested by algal blooms and “fish kills” which create concerns among residents in close proximity to the pond or reservoir. Nutrient overenrichment also reduces the assimilative capacity of the pond or reservoir designed to reduce nutrient contributions to receiving waters. A condition referred to as hypoxia where the dissolved oxygen concentration of less than 2.0 ppm persists is typically the result of nutrient over-enrichment but there are uncertainties as to how basin morphometry may also contribute to hypoxia. Most stormwater design consultants attempt to minimize the size of the basin imprint in residential communities to maximize development density. Minimizing the basin “imprint” is usually accomplished by decreasing the surface to volume ratio resulting in greater maximum depth. Relatively deep basins in southwest Florida are inherently subject to weak thermal stratification but often distinct oxygen stratification that leads to near bottom hypoxia. Bottom strata having hypoxic conditions also contribute to or facilitate the transport of nutrients such as phosphorus back into the water column leading to increased primary production (algae and macrophyte growth). Destratification resulting from vertical mixing by wind can generate hypoxic conditions throughout the water column sometimes causing fish mortality.

The objective of this study was to examine various basin morphometry dimensions with respect to near bottom dissolved oxygen concentrations during late summer when oxygen stratification typically occurs in southwest Florida.

METHODS

Eleven artificial ponds or lakes were chosen with varying basin morphometry to explore the effects of depth and other metrics on oxygen stratification. The individual ponds will be described in detail in the following section.

Multiple transects along each major pond axis were surveyed with a BioSonics Echosounder to determine maximum and average depth of each basin. Surface area and maximum east-west fetch distance was determined from scaled aerial imagery and the use of a polar planimeter. East-west fetch distance was used due to prevailing easterly winds during summer months in southwest Florida. Depth and area measurements were used to calculate pond volume, surface to volume ratio, relative depth Zr, and dynamic ratio for each pond. Pond surface areas and east-west fetch distance were measured initially in 2007 and we assumed the same area and fetch for 2008 and 2009 because basins are typically full or at control elevations late in the wet season. Most of the basins also exhibited relatively steep pond margins that would tend to mitigate the minor variation in late season surface area resulting from pond level changes.

Dissolved oxygen, temperature and specific conductance were measured with the use of a Manta multiprobe at 0.5 meter increments along a vertical profile at each pond maximum depth during late summer (late July through September) in 2007, 2008 and 2009. Average depth and volume were adjusted proportionally from changes in maximum depth in 2008 and 2009. For example, if maximum depth increased 10% from 2007 to 2008 then average depth was increased the same proportion. Volume estimates, Relative Depth (Zr) and Dynamic Ratio were adjusted from the recalculated average depth and respective volume for 2008 and 2009.

Relative Depth Zr is defined as the maximum depth as a percentage of the mean diameter and calculated as: $Zr = 50 \times \max.\text{depth} \times \frac{\sqrt{\pi}}{\sqrt{\text{surface area}}}$. Most lakes have a Zr of less than 2% whereas deep lakes with small surface areas exhibit greater resistance to mixing and usually have a Zr > 4% (Wetzel and Liken 1990). It has been determined that the highest values of Zr are always found in small water bodies, with areas rarely over 1 Km² but low Zr values are easily found in both large and small systems (von Sperling, E. unpub. report). Dynamic ratio is the square root of the lake surface area in square kilometers divided by the mean depth in meters and is useful as a measure of potential wave disturbance on bottom sediments, particle flux and an indicator of water quality in Florida Lakes (Bachmann, R.W. et al. 2000). Typically, Dynamic Ratio is most valid for predicting particle flux and potential proportion of bottom area vulnerable to wind suspension when values are $\geq$ to 0.15 and lake mean depth is $\leq$ to 9m (Weyhenmeyer, G.A. and J. Bloesch, 2001). The highest Dynamic Ratio of the 11 basins studied was 0.13 and as such will be used sparingly in relation to oxygen stratification and other morphometrics used. Lakes studied in Florida with Dynamic Ratio values greater than 0.8 have the entire lakebed subject to wave disturbance (Bachmann, R.W. et al. 2000).

To further refine our understanding of oxygen stratification dynamics through time, we measured, dissolved oxygen, temperature and specific conductance at 0.5 meters above the bottom (maximum depth) at two hour intervals from June 2009 through February 2011 at Site 8. Continuous onsite monitoring was achieved with a Manta multiprobe. A metal rack was constructed to secure the probe vertically about 1 meter above bottom. The probe was retrieved at approximately two week intervals for cleaning, maintenance and data download. Also, at Site 8 we measured dissolved oxygen,

temperature and specific conductance at 0.5 meter increments along a vertical profile at maximum depth about every two weeks during probe maintenance periods.

Site Locations, Descriptions and Morphometry

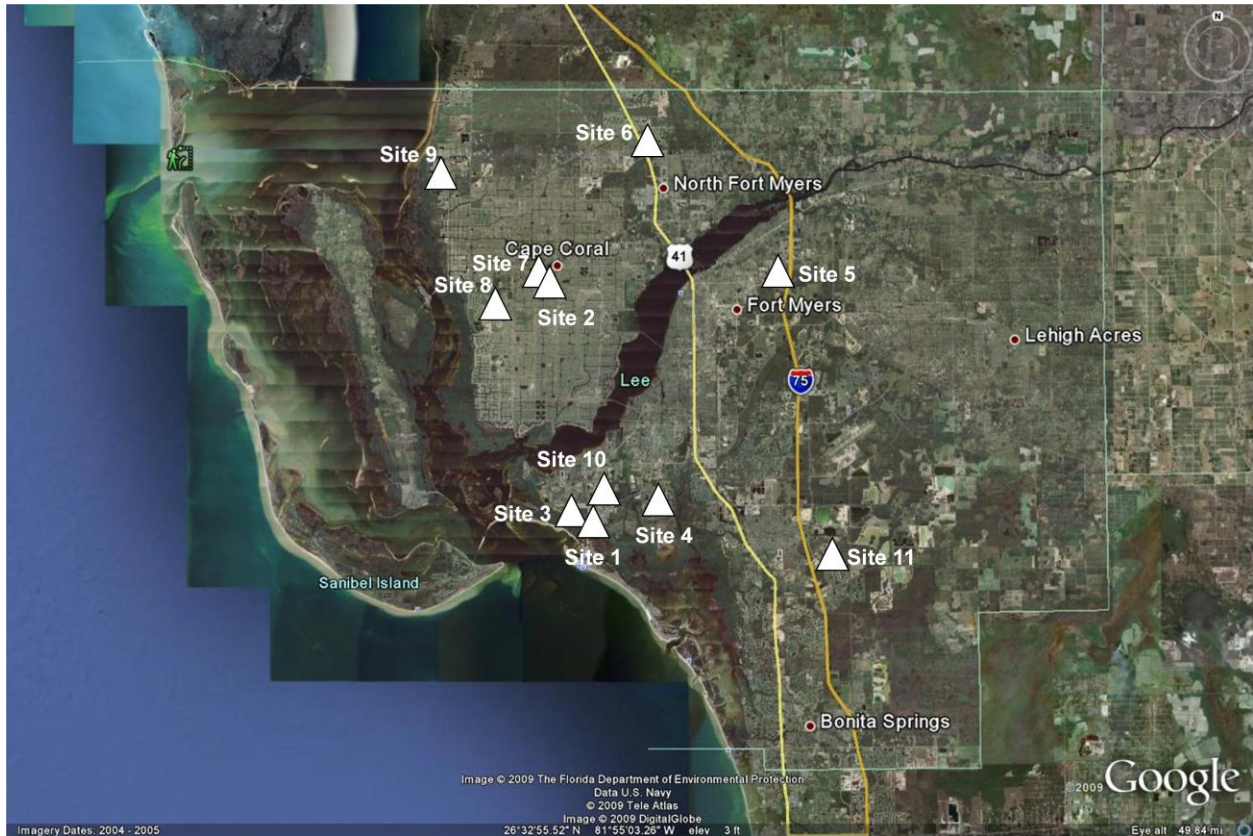


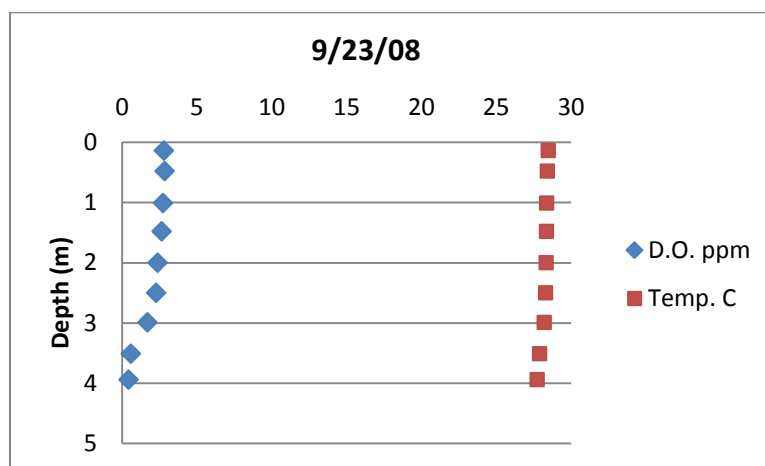
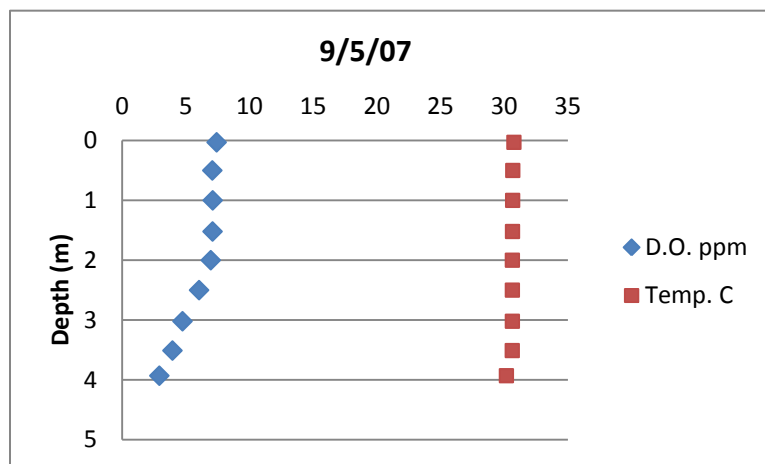
Figure 1. Morphometry study basin locations in Lee County, Florida.

Site 1



Table 1. Site 1 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	1.8	1.8	1.8
Maximum depth (m)	3.9	4.3	3.6
Average depth (m)	2.5	2.7	2.3
Volume (acre feet)	14.8	16.0	13.7
Surface/volume	0.12	0.11	0.13
Relative depth Zr	4.05	4.38	3.74
Dynamic ratio	0.034	0.032	0.037
East –West fetch (m)	85.6	85.6	85.6
Trophic State Index			52.5



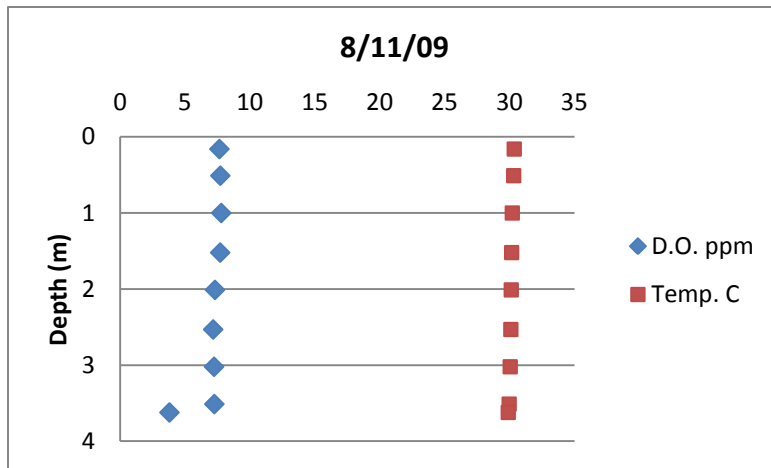


Figure 2. Site 1 D.O. and temperature profiles 2007-2009.

Site 1 is located at Longitude 81°57'.24.2"W; 26°30'.14.7" (Figure 1). This basin represents a relatively small wet detention pond associated with high density residential development. A small surface fountain with a near surface intake is located near the pond center and likely has little effect on vertical mixing of the water column. The outfall is located at the south end of the pond. Pond depth and corresponding volume varied little during the three year study period. This site represented the second shallowest basin for average depth and third shallowest for maximum depth among the 11 studied.

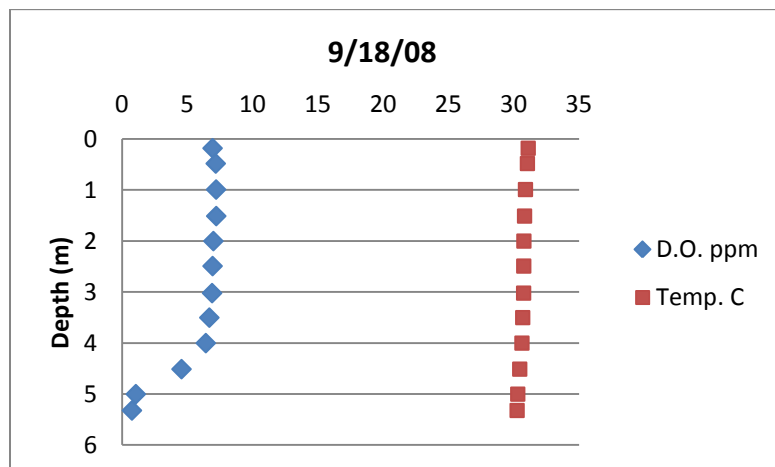
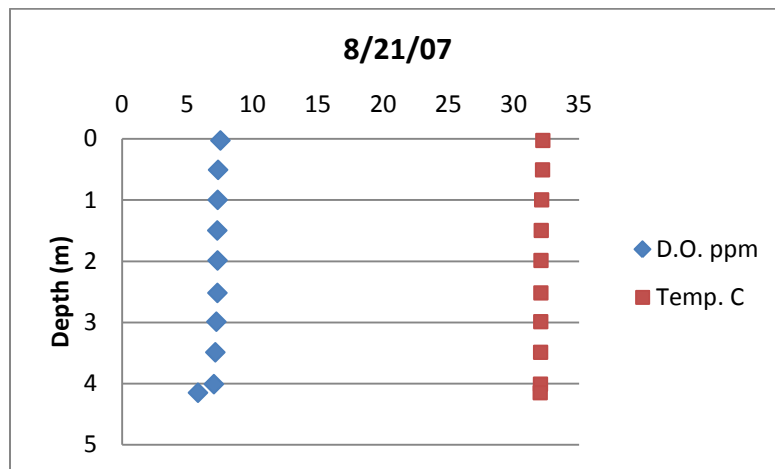
Site 1 has a relatively high surface to volume ratio but the seemingly anomalous Relative Depth index of 4.06 (annual average) normally indicative of a deep lake but paradoxically is often highest in very small water bodies and as such is not a good indicator of mixing in a basin of this size (von Sperling, E. unpub. report). The Dynamic Ratio (.034 annual average) indicates low potential for wind suspension but is a poor indicator of sediment particle flux when below 0.15 (Weyhenmeyer, G.A. and Bloesch, J., 2001). Oxygen concentrations were relatively low during 2007 and 2008 with mild stratification inflection points at 3 m on the vertical profile. A Trophic State Index of 52 is indicative of mid eutrophic conditions.

Site 2



Table 2. Site 2 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	3.3	3.3	3.3
Maximum depth (m)	5.3	5.3	5.0
Average depth (m)	3.6	3.6	3.4
Volume (acre feet)	38.9	38.9	36.3
Surface/volume	0.08	0.08	0.09
Relative depth Zr	4.06	4.07	3.79
Dynamic ratio	0.032	0.032	0.034
East –West fetch (m)	102.7	102.7	102.7
Trophic State Index			41.9



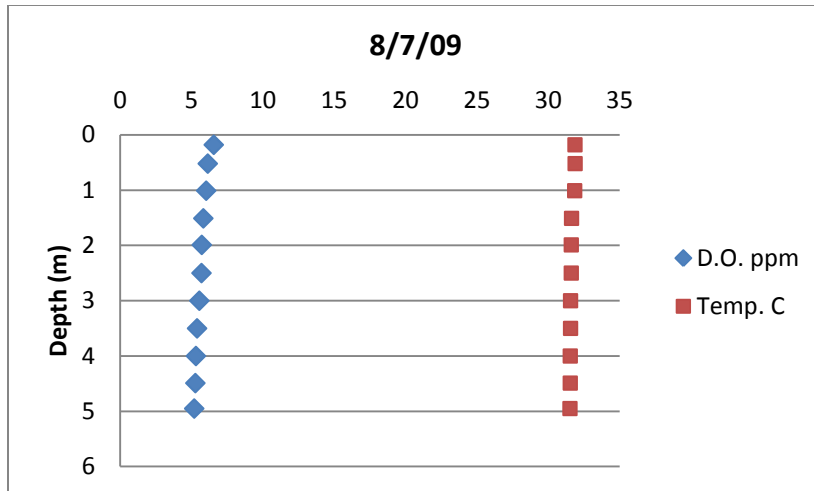


Figure 3. Site 2 D.O. and temperature profiles 2007-2009.

Site 2 is located at Longitude 81°59'41.2"W and Latitude 26°39'22.9"N (Figure 1). The Site 2 basin is located in a low density residential area. It is unclear how stormwater enters and leaves this site. Site 2 is moderately deep and has a mid level surface to volume ratio and Relative Depth index. The east-west fetch distance is relatively minor. Oxygen stratification with values less than 1 ppm near bottom occurred in 2008 but not in 2007 and 2009. The level of eutrophication was mild (good condition) with a Trophic State Index of 41.9. Transparency was also very high at this site with a secchi disc reading of 7 feet 5 inches during August 2009.

Site 3

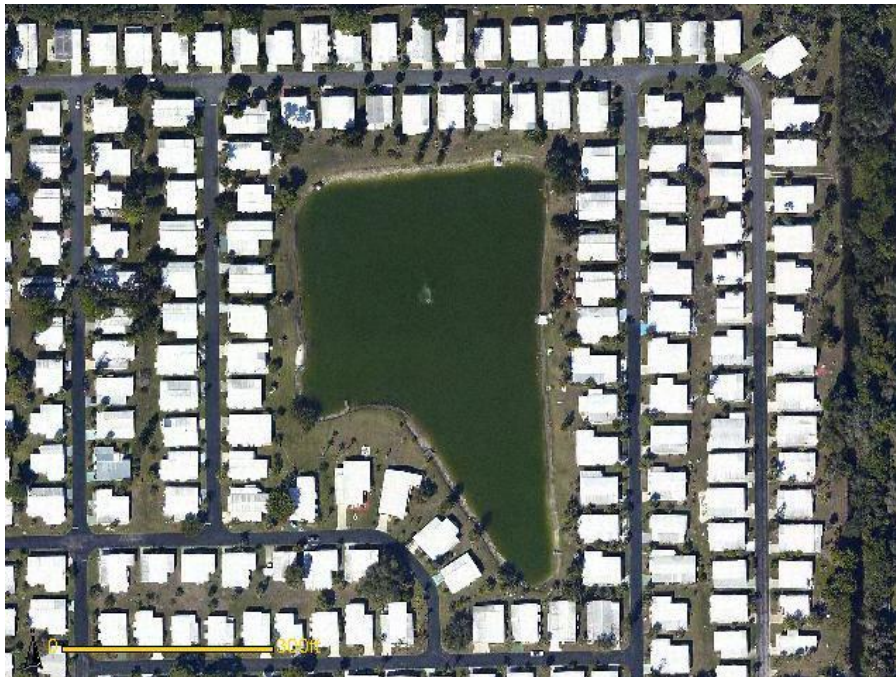
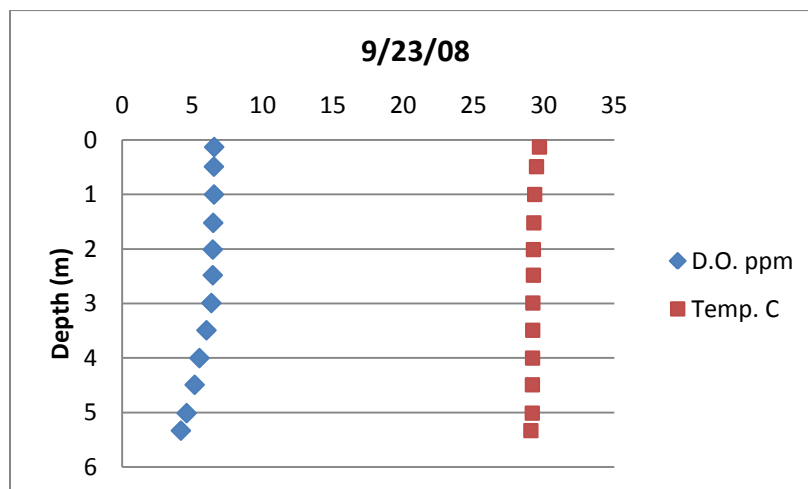
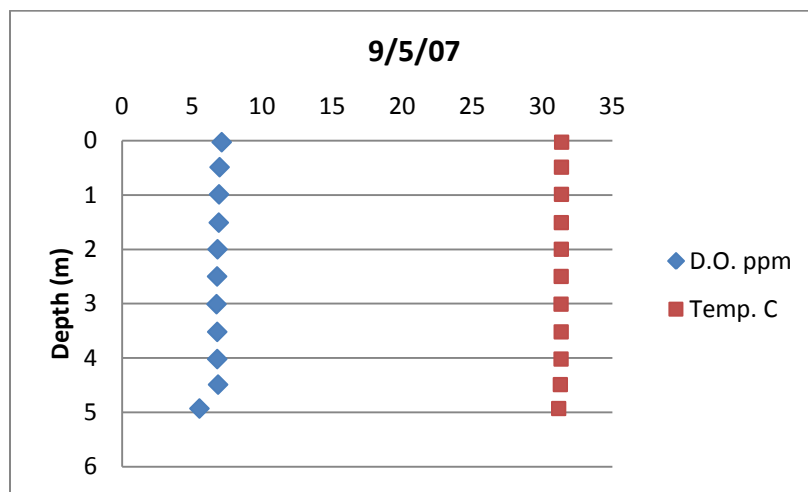


Table 3. Site 3 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	3.5	3.5	3.5
Maximum depth (m)	5.3	5.3	4.4
Average depth (m)	3.05	3.05	2.53
Volume (acre feet)	35.0	35.0	29.1
Surface/volume	0.10	0.10	0.12
Relative depth Zr	3.96	3.94	3.29
Dynamic ratio	0.04	0.04	0.05
East –West fetch (m)	106.6	106.6	106.6
Trophic State Index			42.0



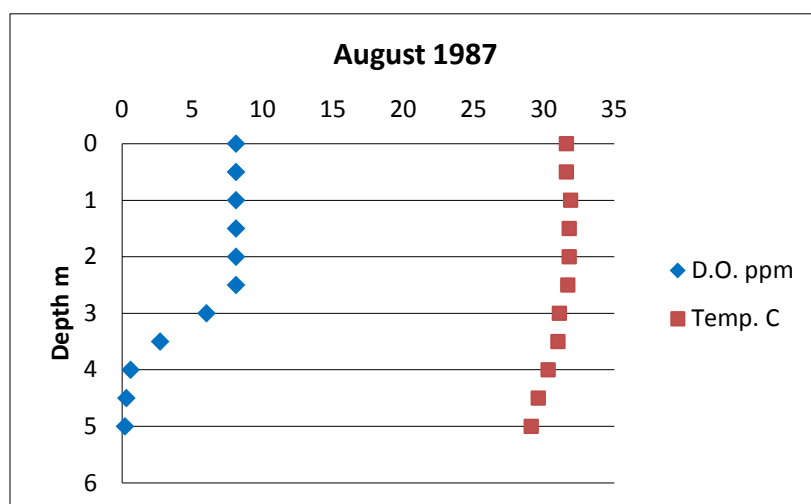
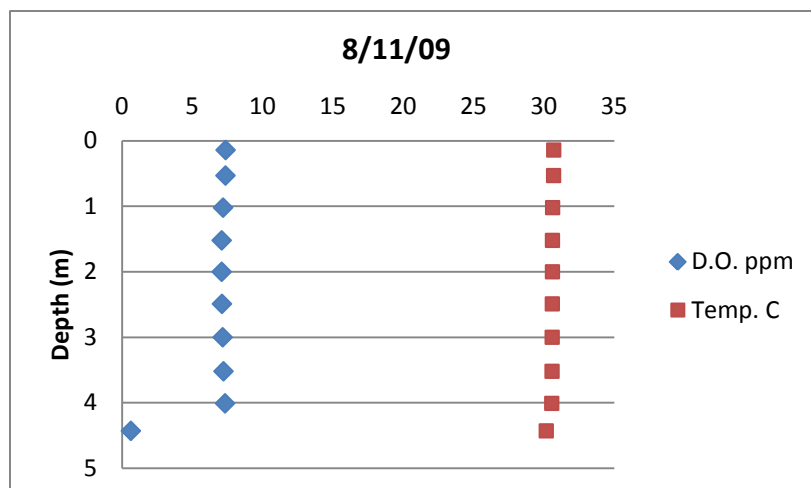


Figure 4. Site 3 D.O. and temperature profiles, 1987, 2007-2009.

Site 3 is located at Longitude 81°57'41.9"W and Latitude 26°30'00.6"N (Fig. 1). It is similar to Site 1 located in a high density residential community. The site had likely been in existence for at least 30 years as of 2009. A surface fountain runs intermittently but does not draw from deeper strata. Maximum and average depth are relatively low. The surface/volume ratio is relatively high. A relatively minor east-west fetch and a dynamic ratio of 0.04 to 0.05 indicates a relatively low potential for wind suspension of the bottom sediments. Oxygen stratification was weak during 2007-2009 however stratification during August of 1987 was extreme due to greater than 80 percent of the pond having cover with submersed aquatic vegetation which is known to inhibit vertical mixing. The Trophic State Index of 42 indicates a low to moderate level of nutrient enrichment.

Site 4



Table 4. Site 4 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	6.7	6.7	6.7
Maximum depth (m)	2.5	2.6	2.1
Average depth (m)	1.4	1.4	1.1
Volume (acre feet)	30.2	30.8	24.8
Surface/volume	0.22	0.22	0.27
Relative depth Zr	1.34	1.38	1.11
Dynamic ratio	0.120	0.118	0.150
East –West fetch (m)	131.7	131.7	131.7
Trophic State Index			57

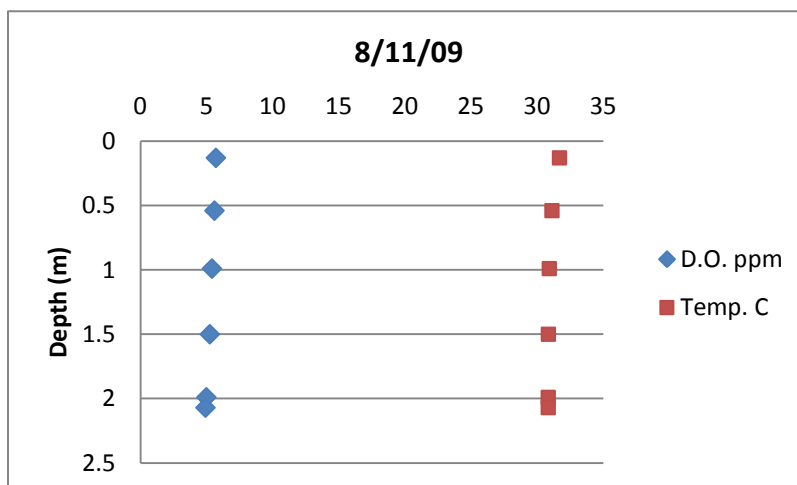
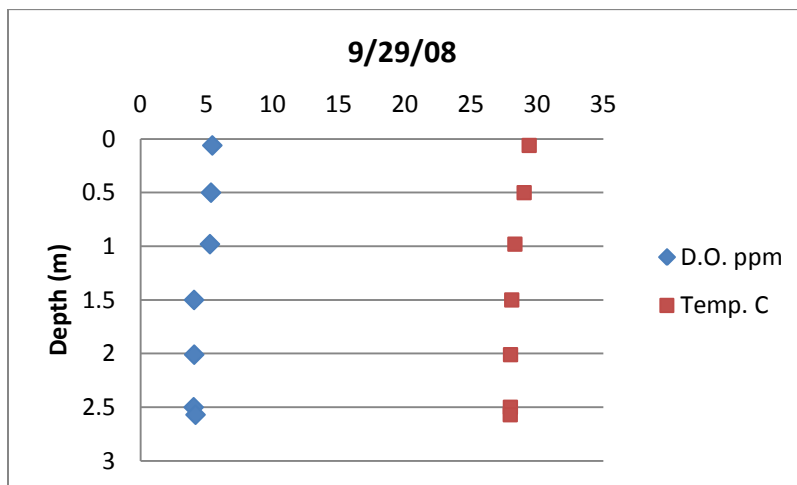
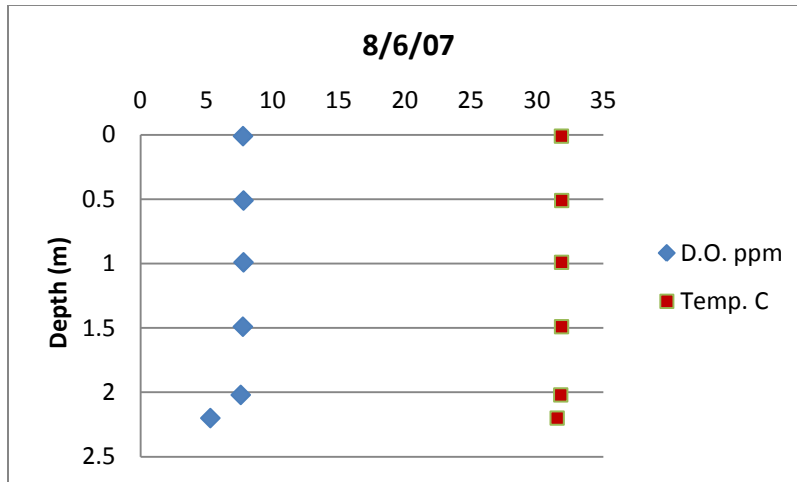


Figure 5. Site 4 D.O. and temperature profiles 2007-2009.

Site 4 is located at Longitude 81°53'05.9"W and Latitude 26°30'54.8"N (Fig. 1). The basin is associated with a moderately dense single family community that has been existence for at least 30 years as of 2009. This site had the lowest average depth and highest surface to volume ratio (avg. 0.24) of the 11

sites studied. Oxygen stratification was essentially non-existent during the study period. The relative depth of 1.11 – 1.38 is more typically indicative of a small lake with a relatively high surface to volume ratio. The Dynamic Ratio at this site was the highest of the 11 sites studied indicating the highest potential for particle flux as would be expected for a shallow basin. The Trophic State Index of 57 was the highest among the 11 sites studied indicating moderate to the low end of high nutrient enrichment.

Site 5



Table 5. Site 5 Characteristics

Parameter	2007	2008	2009
Surface area (acres)	7.0	7.0	7.0
Maximum depth (m)	3.5	4.2	3.2
Average depth (m)	2.7	3.3	2.6
Volume (acre feet)	63.0	76.3	58.8
Surface/volume	0.11	0.09	0.12
Relative depth Zr	1.84	1.22	1.70
Dynamic ratio	0.06	0.05	0.06
East –West fetch (m)	136.9	136.9	136.9
Trophic State Index			43.4

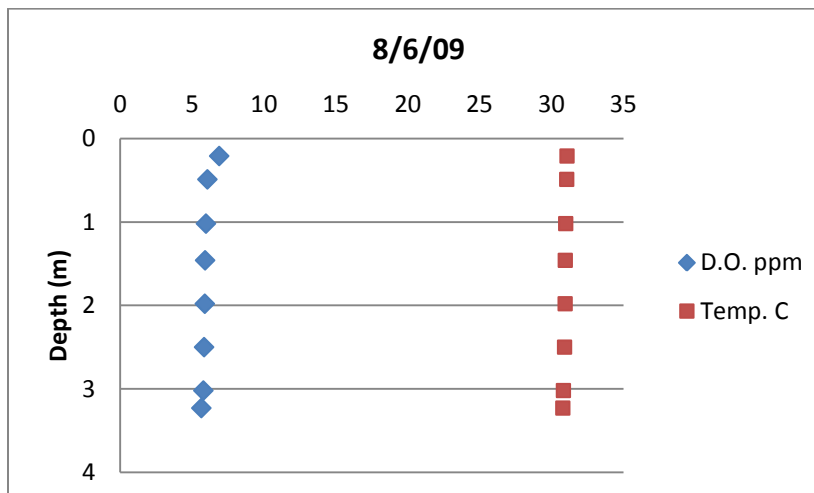
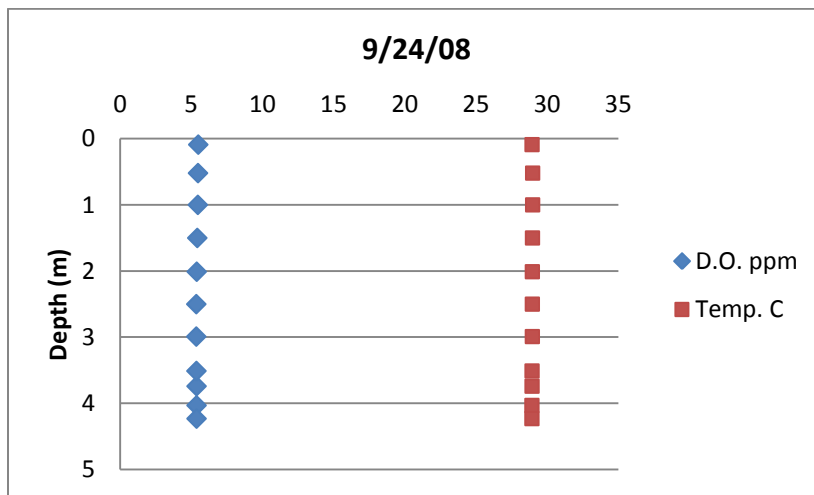
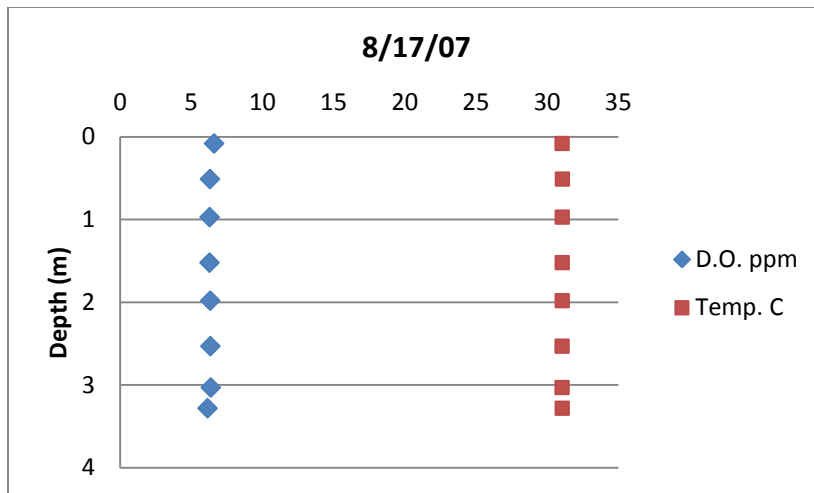
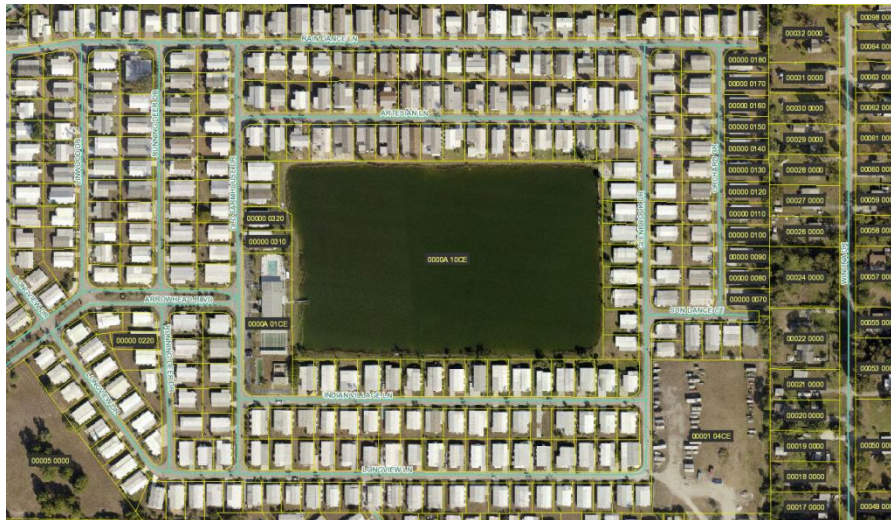


Figure 6. Site 5 D.O. and temperature profiles 2007-2009.

Site 5 is located at Longitude 81°48'08.4"W and Latitude 26°38'39.0"N (Fig. 1). This pond likely originated as an Interstate 75 "borrow pit". The basin is relatively shallow and has a relatively high surface to volume ratio. Relative Depth Zr of 1.77 – 2.20 also indicates a high surface to volume ratio

Site 6



Parameter	2007	2008	2009
Surface area (acres)	9.0	9.0	9.0
Maximum depth (m)	6.3	6.3	5.3
Average depth (m)	4.5	4.5	3.7
Volume (acre feet)	133.2	133.2	109.8
Surface/volume	0.7	0.7	0.8
Relative depth Zr	2.78	2.92	2.44
Dynamic ratio	0.042	0.042	0.052
East –West fetch (m)	248.1	248.1	248.1
Trophic State Index			50.0

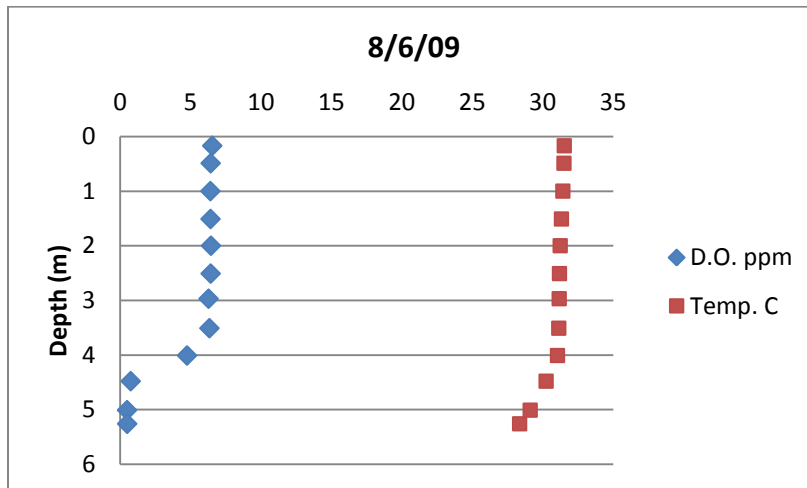
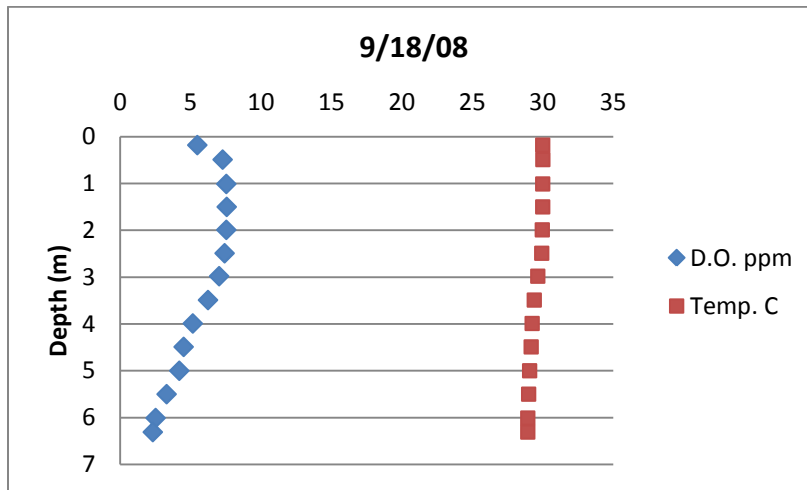
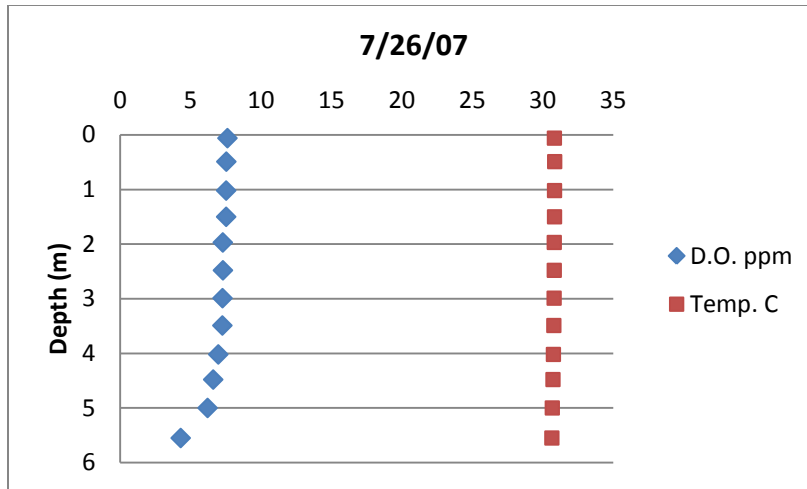


Figure 7. Site 6 D.O. and temperature profiles 2007-2009.

Site 6 is located at Longitude 81°53'38.4"W and Latitude 26°42'34.5"N (Fig. 1). The site is similar to Sites 1 and 3 occurring in a high density single family residential community. The basin is relatively deep having high average depth and maximum depth. The surface to volume ratio is relatively low and the

Relative Depth index reflects a similar condition. Oxygen stratification was evident in August of 2009 but not in 2007 and 2008. The basin has its primary axis in an east-west orientation which would facilitate normally easterly winds during the summer months and oxygen stratification did occur during 2009. A TSI of 50 indicates the high end of a moderately eutrophic condition.

Site 7



Table 7. Site 7 Characteristics.

Parameter	2007	2008	2009
Surface area (acres)	9.7	9.7	9.7
Maximum depth (m)	6.0	6.0	5.2
Average depth (m)	3.6	3.6	3.3
Volume (acre feet)	113.3	113.3	103.8
Surface/volume	0.08	0.08	0.09
Relative depth Zr	2.68	2.68	2.47
Dynamic ratio	0.06	0.06	0.06
East –West fetch (m)	440.4	440.4	440.4
Trophic State Index			53

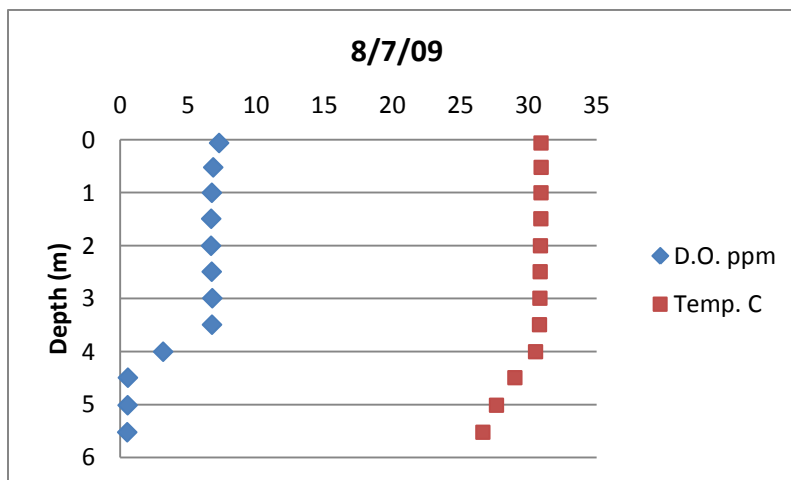
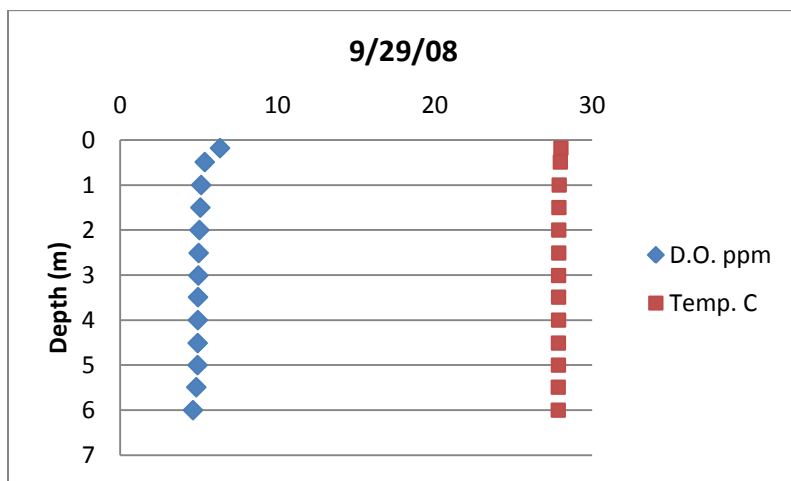
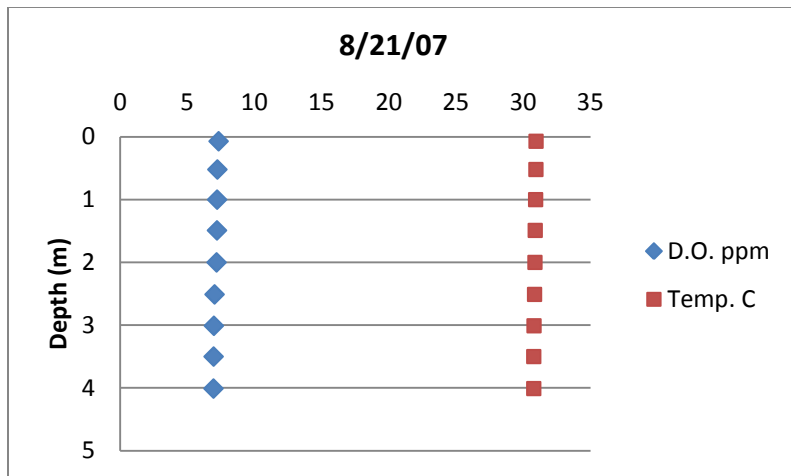


Figure 8. Site 7 D.O. and temperature profiles 2007-2009.

Site 7 is located at Longitude 81°59'35.9"W and Latitude 26°39'31.3"N (Fig. 1). This artificial basin appears to have been excavated for sand or gravel. It has relatively moderate maximum and average depth, Relative Depth and surface to volume ratio. Oxygen stratification only occurred in 2009 and was

abrupt at 3.5 meters. The basin appears to have a relatively small watershed. The TSI index was 53 indicative of moderate eutrophication.

Site 8



Table 8. Site 8 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	28	28	28
Maximum depth (m)	8.5	7.3	7.5
Average depth (m)	3.6	3.1	3.2
Volume (acre feet)	330.4	282.8	291.2
Surface/volume	0.08	0.10	0.10
Relative depth Zr	2.23	1.91	1.98
Dynamic ratio	0.09	0.11	0.11
East –West fetch (m)	293.5	293.5	293.5
Trophic State Index			31.7

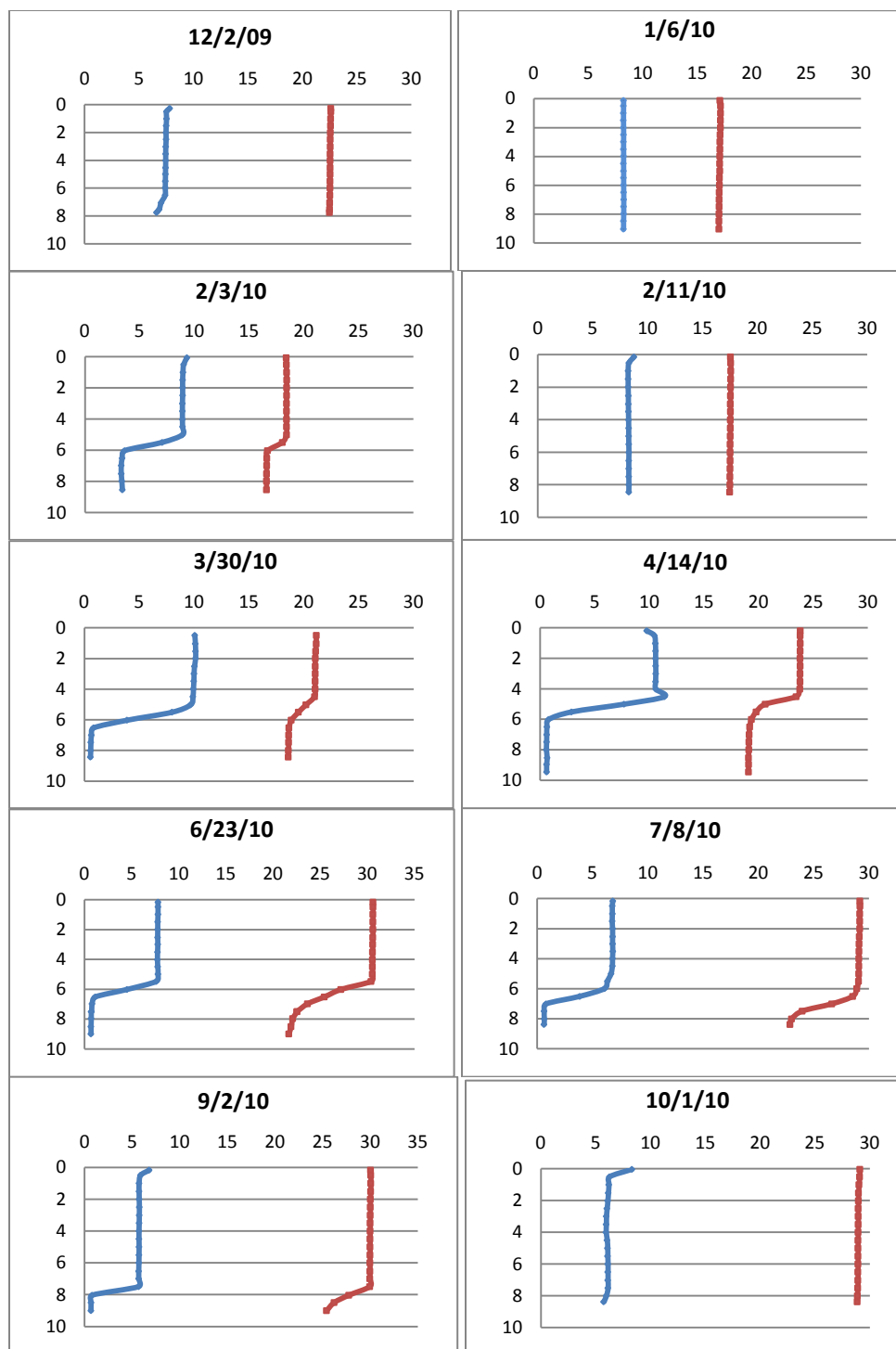


Figure 9. Seasonal sequence of dissolved oxygen (D.O.) and temperature ($^{\circ}\text{C}$) from select vertical profiles at Site 8. D.O. ppm (blue line x axis) and temperature (red line x axis). Y axis is depth in meters.

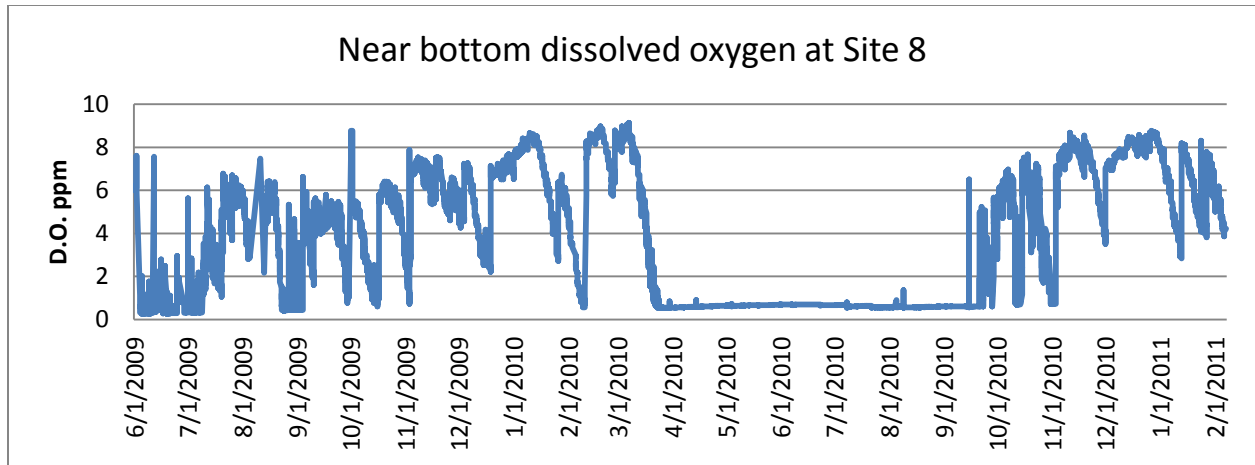


Figure 10. Near bottom dissolved oxygen measured at two hour intervals from June 2009 to February 2011 at Site 8.

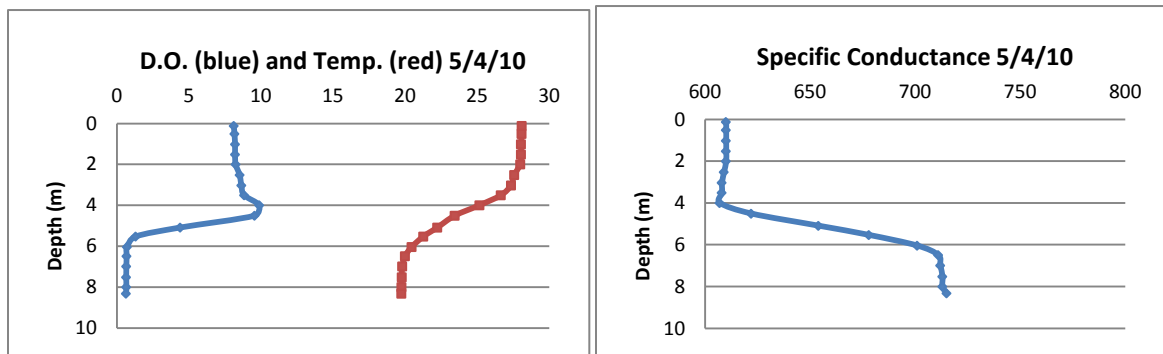


Figure 11. D.O.(ppm) , temperature and specific conductance profiles during early summer seasonal stratification at Site 8.

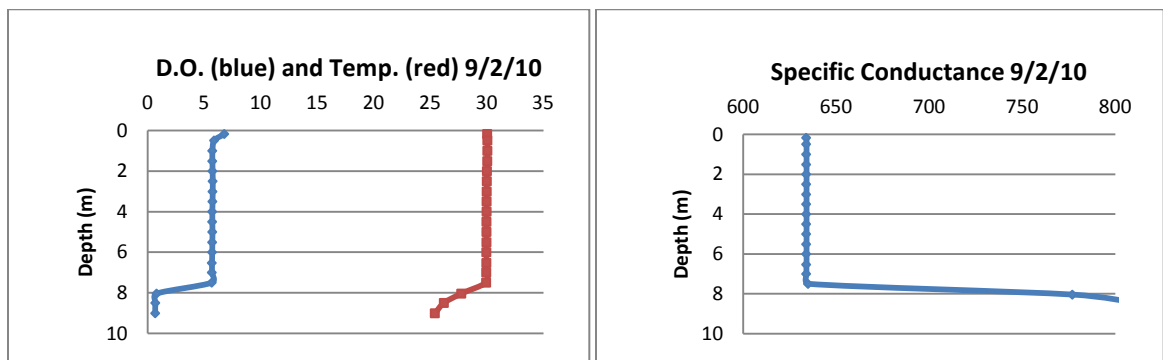


Figure 12. D.O.(ppm), temperature ($^{\circ}\text{C}$) and specific conductance ($\mu\text{S}\cdot\text{cm}^{-1}$) during late summer seasonal stratification at Site 8.

Site 8 is located at Longitude 81°00'34.6"W and Latitude 26°42'34.5"N (Fig. 1). The Site 8 basin is relatively deep with an average annual maximum depth of 7.8 meters. The relative depth, surface to volume ratio and average depth were moderate compared to the other 10 sites. This basin was apparently excavated as a mine site or for fill. It has a steep and narrow littoral area and the catchment appears to be relatively small for a basin of this volume. Very little of the catchment is developed and the level of nutrient enrichment is relatively low with a Trophic State Index of 31.7.

Site 8 was monitored much more extensively compared to the other 10 sites where profiles were measured only once during the late summer season during each of three years (note Methods section for sampling method detail).

Continuous monitoring revealed two distinctly different patterns of vertical oxygen stratification were evident. From the beginning of monitoring on June 1, 2009 until about March 17, 2010, the duration of near bottom hypoxia or vertical oxygen stratification was quite variable but sustained hypoxia (< 2.0 ppm) near bottom did not last longer than about three weeks at any one time (Fig. 10). The other distinct pattern is represented by nearly constant vertical oxygen stratification or near bottom hypoxia and is evident from March 17, 2010 until September 21, 2010, where near bottom D.O. remained at a nearly constant 0.55 – 0.70 ppm. By the first week of October, 2010, near bottom D.O. returned to a somewhat variable pattern but remained above 2.0 ppm until monitoring was terminated during the first week of February 2011 (Fig. 10).

During the extended period of oxygen stratification in 2010, the point in the water column where the oxygen concentration changes abruptly (inflection point) continued to drop during the seasonal period of stratification. At the earliest onset of seasonal oxygen stratification the inflection point occurred at the 4.5-5.0 meter depth increment declining to 7.5 meters by early September (Fig. 9). This has significance for the bottom strata and corresponding volume of the basin that is hypoxic. During the earliest stage of seasonal stratification, hypoxic conditions represent the strata below about 5 meters or about 38 percent of the basin volume. At the end of the oxygen stratification period the near bottom hypoxic strata volume is reduced to about 13 percent of the basin volume. The vertical temperature pattern closely matches the vertical D.O. pattern and accounts for the thickening of the upper strata or epilimnion as that strata progressively warms and expands deeper during the summer months.

The period where both temperature and oxygen stratification are most stable (requiring the most energy to destabilize) is when surface and bottom temperatures are most disparate. This period during 2010 occurred during the first week of June when the difference between surface and bottom temperatures was 11°C. As the epilimnion expands downward the temperature difference between top and bottom declines to a difference of 3°C during the second week of September, setting up the transition to destratification on October 1, 2010 (Fig. 9).

It should be noted that near bottom hypoxia or vertical oxygen stratification can occur after extended cold periods and lasting for periods of at least a week during the coldest months of the year as occurred in February 2010 where surface and bottom temperature occurred in the range of 15-20 °C (Fig. 9).

Site 9

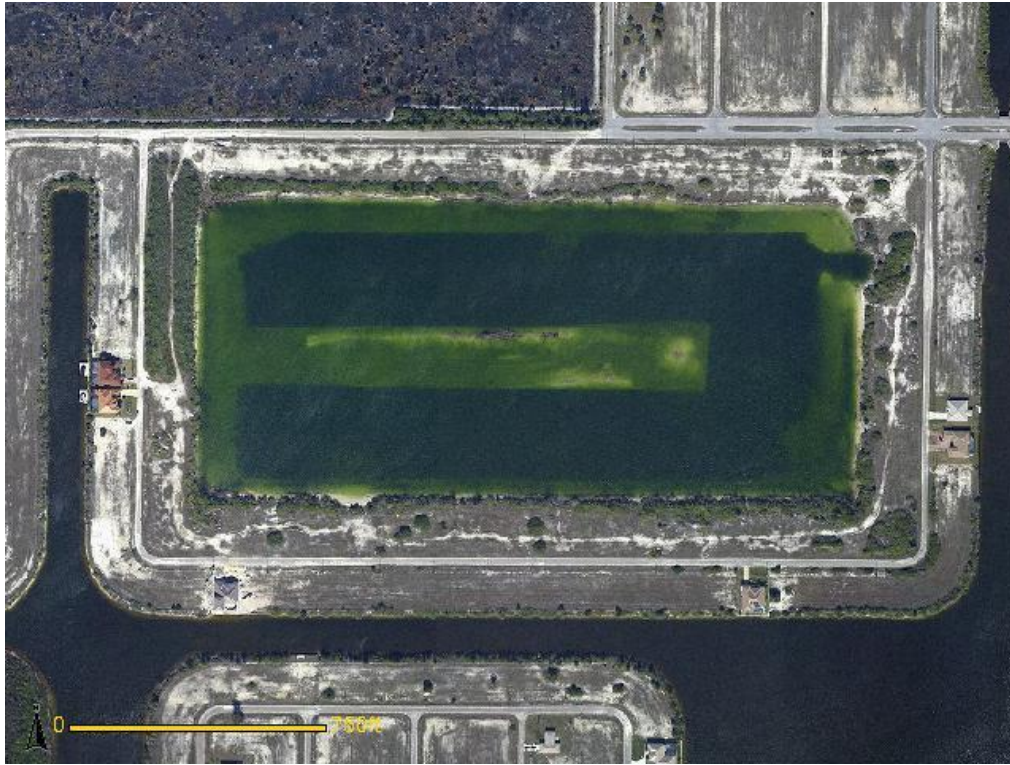


Table 9. Site 9 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	39	39	39
Maximum depth (m)	8.6	8.8	8.3
Average depth (m)	6.1	6.3	5.9
Volume (acre feet)	783.9	802.7	760.5
Surface/volume	0.05	0.05	0.05
Relative depth Zr	1.92	1.96	1.86
Dynamic ratio	0.06	0.06	0.07
East –West fetch (m)	585.2	585.2	585.2
Trophic State Index			24.4

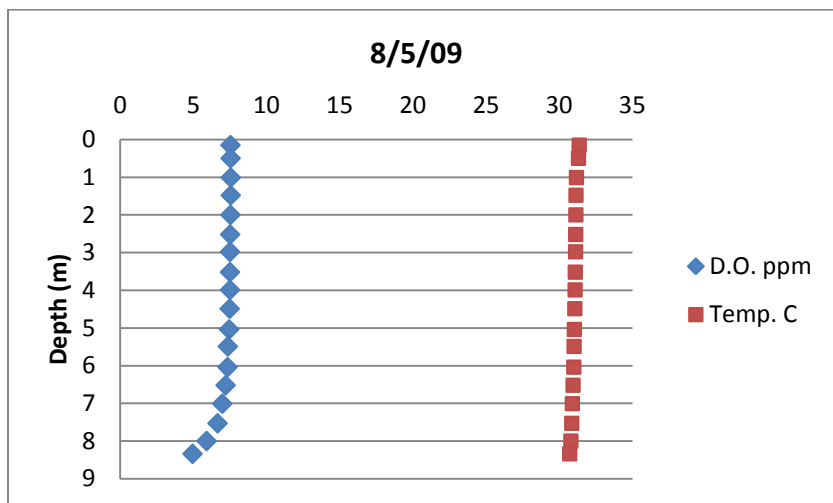
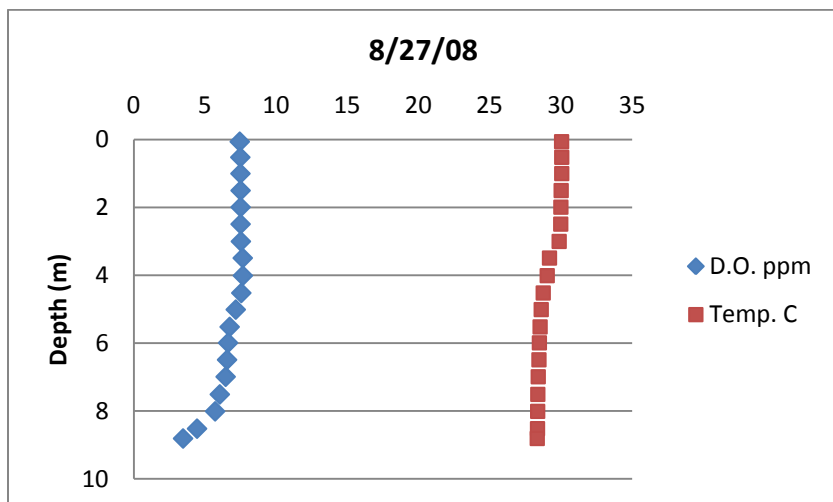
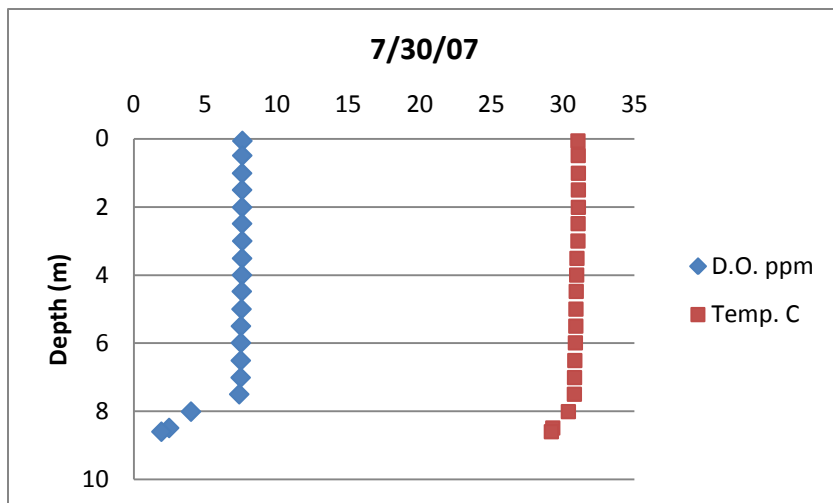


Figure 13. Site 9 D.O. and temperature profiles, 2007-2009.

Site 9 is located at Longitude 82°03'35.9"W and Latitude 26°39'50.3"N (Fig. 1). This basin had the deepest maximum depth and second highest average depth of the 11 basins studied. Basin excavation was likely for fill or to mine sand and gravel. There is a conspicuous shallow area running parallel to the primary axis in the center of the lake which was apparently used to facilitate excavation. Oxygen stratification was minor in 2007 and less so in 2008 and 2009. The elongated east-west orientation maximized the effect of prevailing wind during the summer and likely facilitated vertical mixing. This basin has a very small watershed and likely receives minimal stormwater runoff and nutrient loading. Most of the water and nutrient budget is likely driven by groundwater interactions. The TSI of 24.4 was the lowest of the 11 basin study group indicating oligotrophic conditions.

Site 10



Table 10. Site 10 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	49	49	49
Maximum depth (m)	7.9	8.0	7.6
Average depth (m)	4.48	4.48	4.27
Volume (acre feet)	720.3	720.3	686.0
Surface/volume	0.07	0.07	0.07
Relative depth Zr	1.57	1.58	1.50
Dynamic ratio	0.10	0.10	0.10
East –West fetch (m)	765.7	765.7	765.7
Trophic State Index			50.2

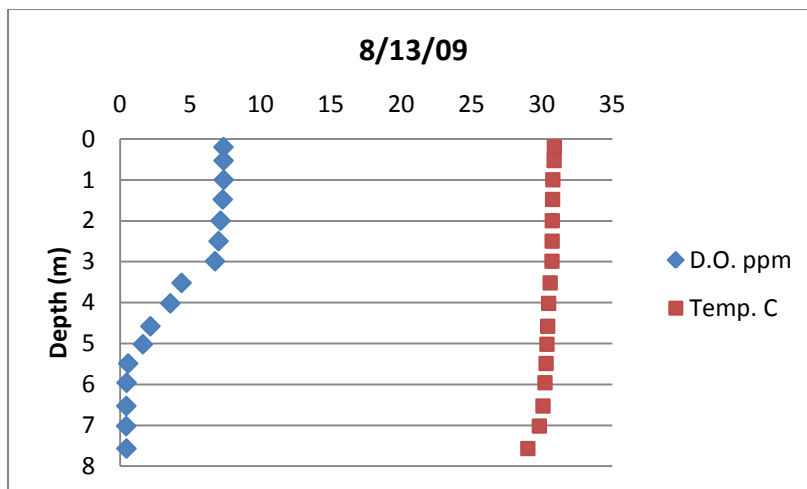
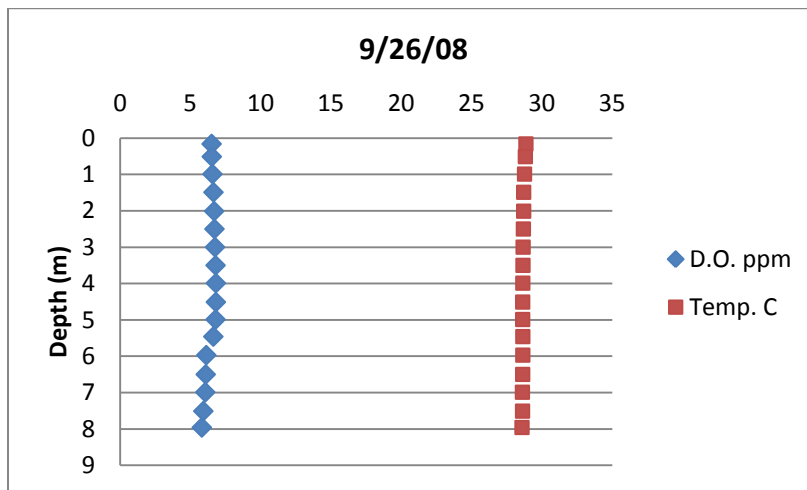
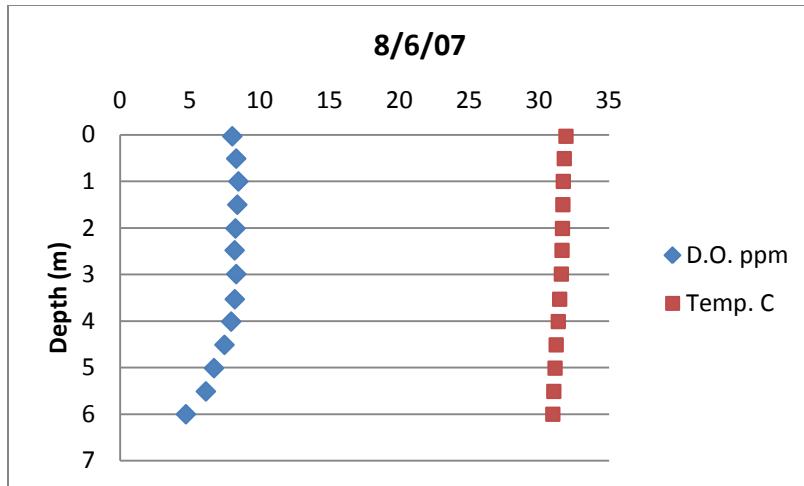


Figure 14. Site 10 D.O. and temperature profiles, 2007-2009.

Site 10 is located at Longitude 81°55'52.0"W and Latitude 26°31'19.7"N (Fig. 1). The basin at this site had the second largest surface area of the 11 studied. Maximum and average depth were also relatively

high. Vertical oxygen stratification occurred when measured in 2009 but not in 2007 and 2008. Eutrophication or nutrient enrichment was moderate with a TSI of 50.2 when measured in 2009.

Site 11



Table 11. Site 11 characteristics.

Parameter	2007	2008	2009
Surface area (acres)	134.0	134.0	134.0
Maximum depth (m)	8.3	8.4	8.7
Average depth (m)	7.25	7.25	7.56
Volume (acre feet)	3189.2	3189.2	3323.2
Surface/volume	0.04	0.04	0.04
Relative depth Zr	1.00	1.01	1.05
Dynamic ratio	0.10	0.10	0.10
East –West fetch (m)	878.7	878.7	878.7
Trophic State Index			44.0

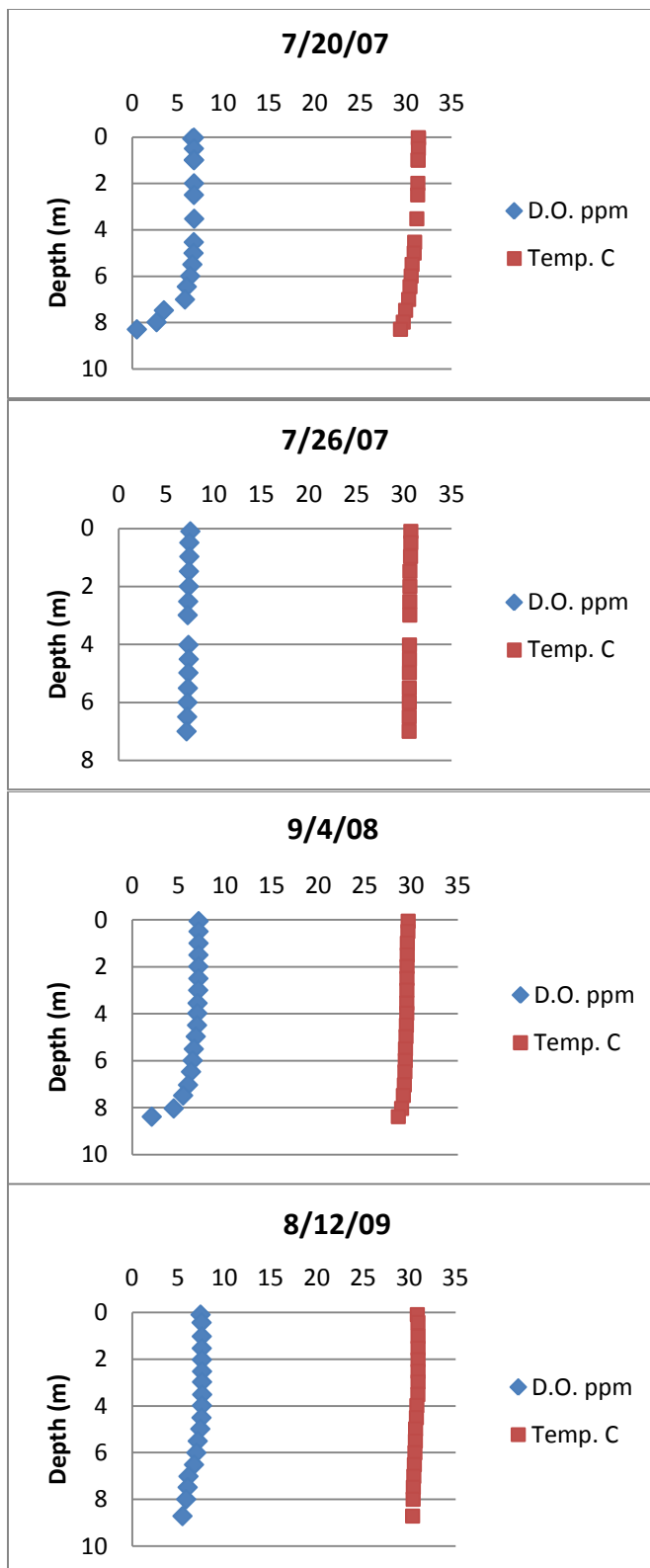


Figure 15. Site 11 D.O. and temperature profiles 2007-2009.

Site 11 is located at Longitude 81°46'13.1"W and Latitude 26°28'29.8"N (Fig. 1). Site 11 had the largest surface area, the highest average depth, the lowest surface to volume ration. This basin was excavated for construction fill and in some areas has an almost vertical gradient very close to the shore. Two vertical profiles were determined in 2007, the first on 7/20/07 and the second six days later. The earlier profile demonstrated vertical oxygen stratification but not again six days later. Vertical oxygen stratification was slight in 2008 and not present in 2009. Nutrient enrichment was relatively low with a TSI of 44.

Analysis of Basin Morphometry Parameters

The following Figures represent least squares linear regressions of individual morphometric parameters as they co-vary, usually with bottom D.O. for the 11 basins studied. Individual data points regressed were the average of the three sampling years (n=3). For basins that did not stratify every year, which was the majority, the average bottom D.O. would always be higher than the minimum D.O. that occurred during a year when stratification did occur. Using average bottom D.O. was thought to be more representative of what resulted in a somewhat variable inter-year condition.

Average Bottom D.O. vs. Average Depth

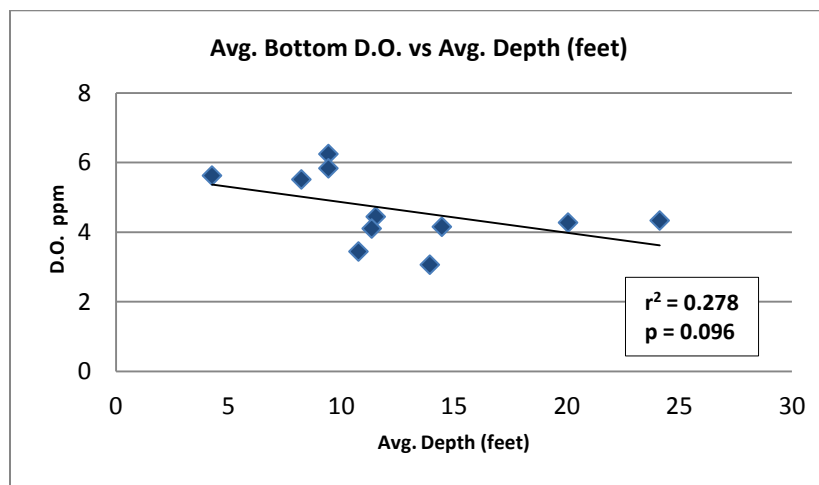


Figure 16. Linear regression of average bottom D.O. and average depth.

$$\text{Bottom D.O.} = 5.9049 - 0.0987 \times \text{Avg. Depth (feet)}$$

A negative or inverse relationship existed between average depth and bottom D.O. The probability of predicting bottom D.O. from average depth was less than the 0.05 probability level (statistical significance level) but relatively close at 0.10. Several basins had somewhat variable bottom depth contours which confounded the use of average depth as a predictor of near bottom anoxia.

Average Bottom D.O. vs. Avg. Maximum Depth

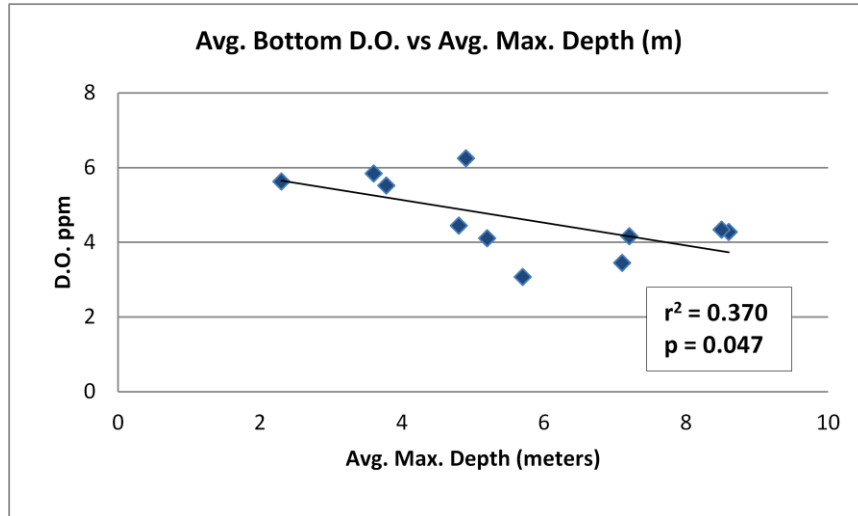


Figure 17. Linear regression of average bottom D.O. and maximum depth.

$$\text{Bottom D.O.} = 6.3512 - 0.3042 \times \text{Max. Depth (m)}$$

An inverse or negative relationship existed between near bottom D.O. and maximum depth. This relationship was statistically significant at the 0.05 level. In general, basins with a maximum depth less than 5 meters did not have an average D.O. value less than 4.0 ppm during the late summer months in 2007-2009. However, the two deepest basins also did not have average values below 4.0 ppm which might be explained by the relatively large fetch associated with these deeper basins.

Average Bottom D.O. vs. Avg. Surface/Volume

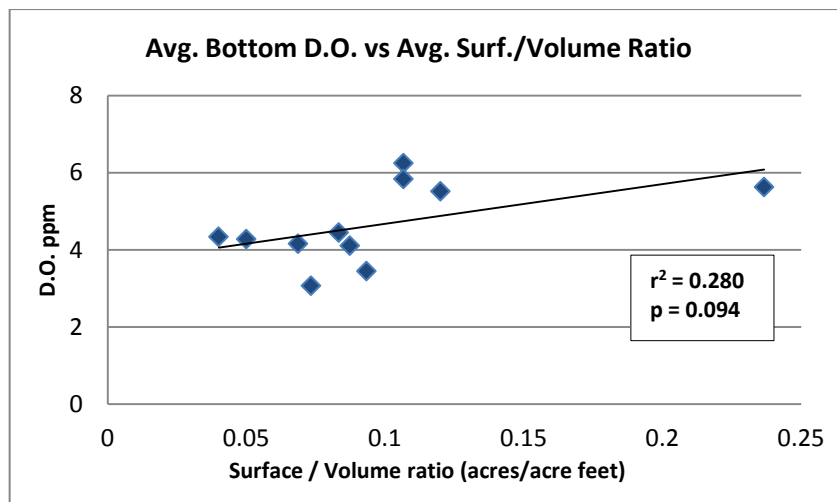


Figure 18. Linear regression of average bottom D.O. and surface/volume ratio.

$$\text{Bottom D.O.} = 3.6439 + 10.335 \times \text{surf./volume}$$

Surface to volume ratio also demonstrated a relatively strong but positive relationship with near bottom D.O. The relationship was not statistically significant but relatively high. Again the high variability of bottom contour and corresponding depth reduced the predictability of surface to volume ratio to bottom D.O. We suspect a larger sample size would have made surface to volume ratio a good predictor of bottom D.O.

Average Bottom D.O. vs. East/West Fetch (m)

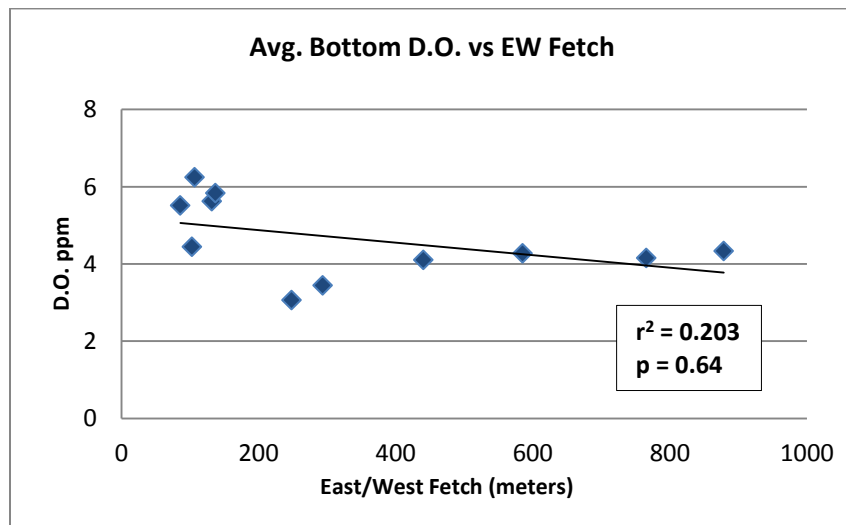


Figure 19. Linear regression of average bottom D.O. and East/West oriented fetch distance (m).

$$\text{Bottom D.O.} = 5.2000 - 1.6200 \times \text{east/west fetch (m)}$$

The relationship between fetch distance and near bottom D.O. was weak and not significant. Basins with the longest fetch also were typically the deepest (Fig. 23). The longer fetch may compensate for greater depth with respect to declining D.O. as depth increases. There was a significant positive relationship between fetch and maximum depth further substantiating this theory and is presented below (Fig. 23).

Average Bottom D.O. vs. Relative Depth Zr

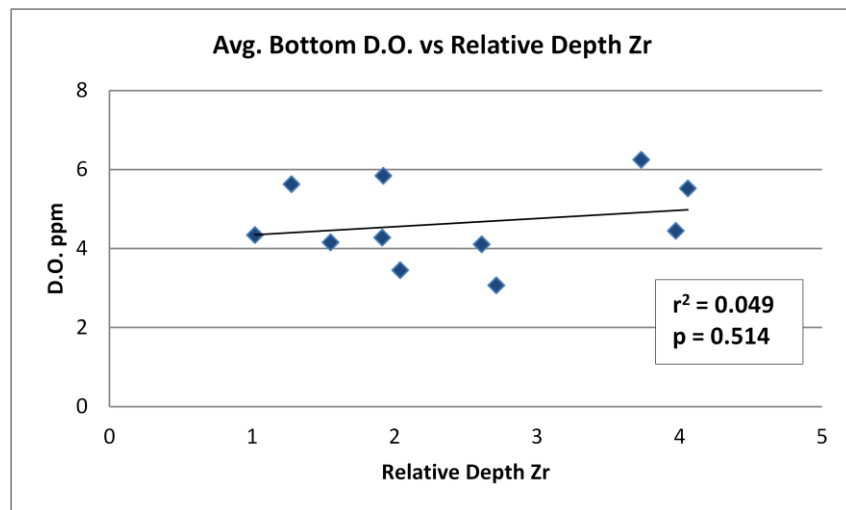


Figure 20. Linear regression of average bottom D.O. and Relative Depth Zr.

$$\text{Bottom D.O.} = 4.1346 + 0.2096 \times \text{Zr}$$

Relative Depth Zr (maximum depth as a percentage of the mean diameter) was a poor predictor of near bottom D.O. in the artificial basins studied. A very weak positive relationship resulted from the relationship of bottom D.O. with this parameter.

Average Bottom D.O. vs. Trophic State Index (TSI)

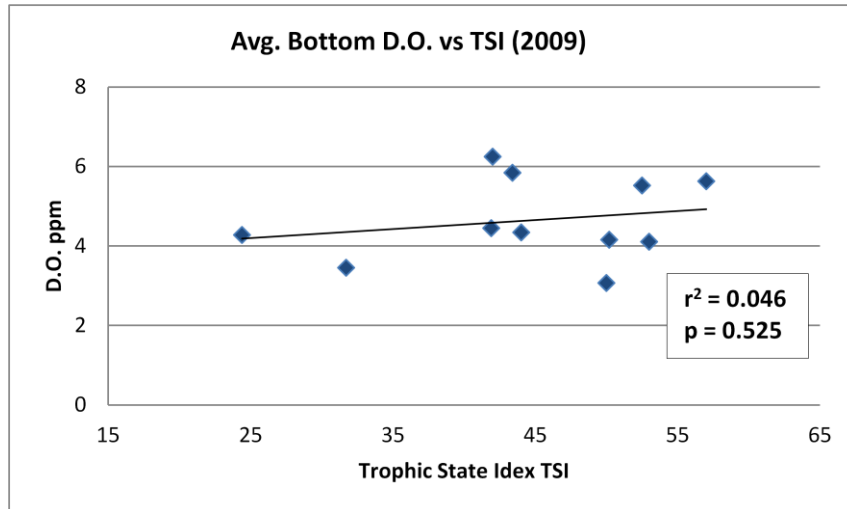


Figure 21. Linear regression of average bottom D.O. and TSI.

$$\text{Bottom D.O.} = 3.6331 + 0.0227 \times \text{TSI}$$

Trophic State Index is a measure of nutrient enrichment in a lake or pond incorporating nitrogen, phosphorus and chlorophyll a into the index equation. The index is a 100 point scale where of 0-59 is considered low or “good” resource quality (oligotrophic thru mid eutrophic); 60-69 is “fair”(mid-eutrophic thru eutrophic); 70-100 “poor” (eutrophic thru hyper-eutrophic). None of the lakes assessed as part of this study had TSI values greater than 57 (as measured in 2009). Of the 11 basins studied, TSI was a poor indicator of near bottom D.O. This is not unexpected since many basins with high or eutrophic conditions have high productivity near the surface where phytoplankton create relatively high D.O. from photosynthesis in the near surface photic zone during daylight hours. As such high D.O. can exist in the upper strata while very low D.O. may occur near the bottom.

Average Bottom D.O. vs. Dynamic Ratio

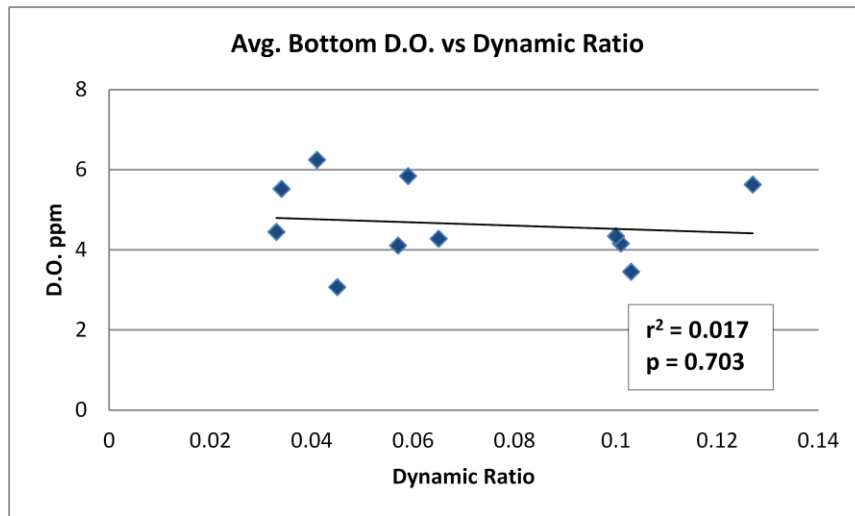


Figure 22. Linear regression of average bottom D.O. and Dynamic Ratio.

$$\text{Bottom D.O.} = 4.9284 - 4.0678 \times \text{Dynamic Ratio}$$

As an indicator of vertical mixing, Dynamic Ratio (square root of the lake surface area in square kilometers divided by the mean depth in meters) is most valid when values are $\geq$ to 0.15. The highest value for Dynamic ratio among the basins studied was 0.13. There is no statistical relationship between Dynamic ratio and Avg. Bottom D.O. was a poor indicator of near bottom hypoxia among the basins studied.

East/West Fetch distance vs. Average Maximum Depth

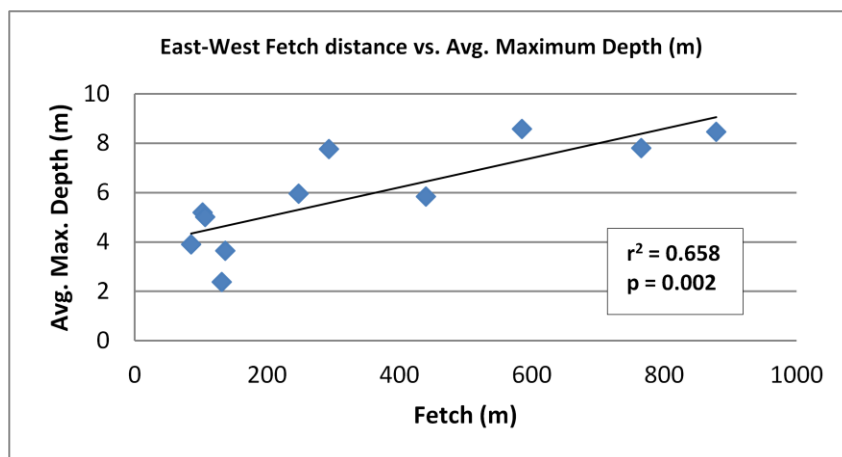


Figure 23. Linear regression of East/West Fetch distance and Avg. Max. Depth

$$\text{Avg. Max. Depth} = 3.8301 + 5.94 \times \text{E/W Fetch (m)}$$

Fetch and maximum depth demonstrated a strong direct positive relationship among the 11 basins studied. Even though maximum depth was a relatively good indicator of near bottom hypoxia, basins that were relatively deep also had correspondingly greater fetch. Basins with a relatively high fetch

would be expected to have greater vertical mixing from wind and may explain why some of the deepest basins (Sites 8-11) demonstrate only minor or intermittent oxygen stratification and hypoxia during the months of July through September.

Avg. Maximum Depth vs. Avg. Surface/Volume

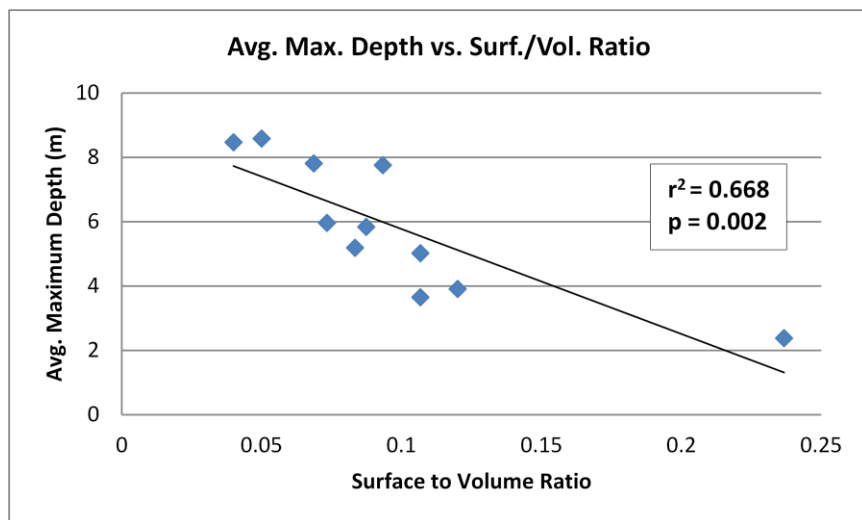


Figure 24. Linear regression of Avg. Max. Depth and Surface/Volume

$$\text{Avg. Max. Depth} = 9.0328 - 32.637 \times \text{Avg. S/V}$$

Maximum depth demonstrated a strong inverse relationship to surface/volume ratio (S/V) among the basins studied. Surface to volume ratio was a moderate but statistically insignificant indicator of bottom hypoxia (Fig. 18).

Discussion

Hypoxia or anaerobic conditions at the sediment water interface in ponds and lakes has important implications for nutrient transport to the water column where nitrogen and phosphorus is utilized by primary producers and other biota. Under anaerobic conditions bacterial decomposition of organic matter promotes a reducing environment where phosphorus is chemically “unbound” from calcium and iron and becomes biologically available in the water column (Fig. 25). This process is sometimes referred to as internal nutrient loading. Often older ponds or lakes have accumulated enough nutrient enriched organic material in their sediments that internal loading can exceed external contributions on an annual basis.

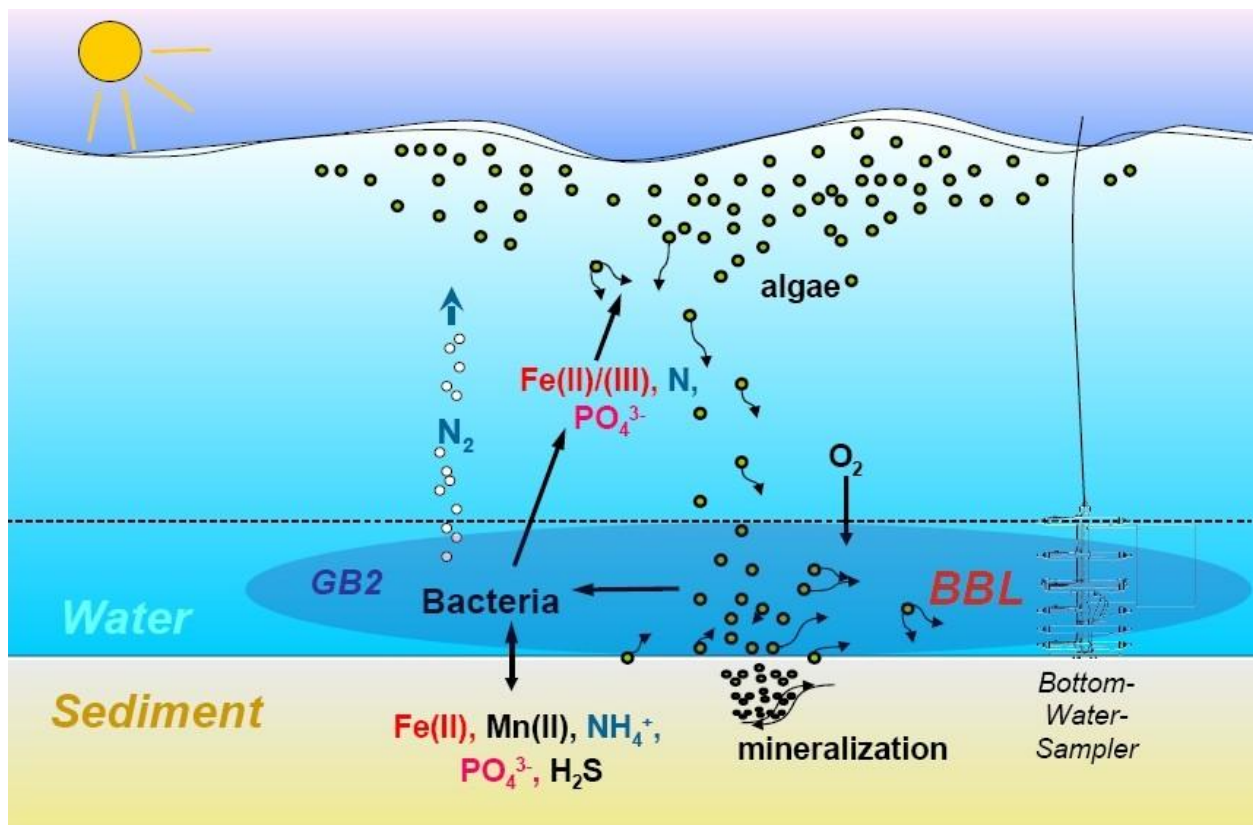


Figure 25. Lake metabolism at the sediment water interface.

Situations where a hypoxic layer represents a significant component of the basin volume, destratification can lead to a severe depression of the entire water column D.O. concentration causing fish kills. Bottom hypoxia is a relatively common condition in artificial basins located in coastal southwest Florida. The seasonal occurrence, duration and extent of the bottom hypoxic layer was found to be highly variable and likely resulting from complex interactions between basin morphometry, climate, degree of wind impacting the basin surface and the conductivity of groundwater as influenced by the proximity to coastal saline waters.

Where late summer vertical transects of D.O. and temperature were measured annually between 2007, 2008 and 2009, oxygen stratification resulting in a bottom hypoxic layer demonstrated three outcomes relating to the frequency and distinctness of the hypoxic bottom layer. Sites 1, 2, 6 and 11 had relatively

minor or a gradual reduction in oxygen concentration from surface to bottom during at least one of the three years studied and similar to the profile illustrated in Figure 15. Sites 3, 7, 8, 9 and 10 demonstrated distinct oxygen stratification at least one of the three years studied (Fig. 8). Site 3 was an anomaly where distinct stratification occurred when measured in 1987 as a part of a previous study at which time the water column was dominated by a submersed aquatic macrophyte which inhibited vertical mixing and promoted a stratified condition. Site 4 and 5 did not demonstrate oxygen stratification during the 2007-2009 period of study.

In this study distinct thermal stratification was only evident at Site 8 (Fig. 9), one of the deeper basins and appeared to coincide with the same vertical inflection points as with dissolved oxygen as is typical of temperate lakes with defined epi and hypolimnetic layers. More frequent profile sampling during the summer months at the other deeper basins, Sites 9-11 (avg. maximum depth > 7.8 m) where oxygen stratification was relatively infrequent, may have revealed thermal stratification similar to Site 8. It is important to emphasize that oxygen stratification resulting in a bottom hypoxic layer can occur without thermal stratification and was a common outcome in both relatively shallow and deep basins (Fig. 3, 4, 7, 14, 15). It appears that bacterial respiration in the sediments and the influence of saline groundwater either acting independently or together create the bottom hypoxic layer often independent of thermal stratification.

At Site 8 where vertical profiles and continuous near bottom monitoring of D.O. and temperature were measured from June 2009 to February 2011, two patterns of oxygen stratification were evident. Oxygen stratification leading to a hypoxic layer was intermittent and typically lasting only a few days up to a week from June through November 2009 and once during February 2010. From late March 2010 through September 2010 oxygen stratification was continuous and near bottom D.O. remained hypoxic (Figures 9 and 10). During this same period of continuous monitoring, oxygen stratification resulting in a bottom layer of hypoxic water occurred at least once during every month except December and January.

The bi-weekly vertical profile monitoring at Site 8 during 2010 when the hypoxic layer was continuous from June through September provided a means of measuring the intact but dynamic nature of the hypoxic layer during the summer season. The depth at which the hypoxic layer begins is relatively shallow during the early summer months of March and April and occurs progressively deeper in the water column as the near surface and mid depth waters continue to warm into early September (Fig. 9). Thus the upper boundary of the hypoxic layer deepens and correspondingly its stability weakens, requiring less energy to destabilize late in the season where complete mixing (a "turnover") generally occurs by early October (Fig. 9). A similar seasonal pattern is also characteristic of temperate lakes. However, Lewis, 1987, states that this pattern of widening of the upper mixed layer and loss of layering stability is not always the case in tropical lakes which are more sensitive to wind stress and changes in heat content resulting from minimal Coriolis effect and low maximum stability and high response to heat content. Furthermore, tropical lakes are different in that convection caused by heat loss may be greater than temperate lakes because higher density changes accompany a given heat loss when water temperature is high (Lewis 1987). Low maximum stability and relatively high response to heat content and wind stress may explain the apparent prevalence of multiple mixing events during the summer of 2009 at Site 8 (Fig. 10).

At Site 8, maximum depth was slightly greater during 2010 and may have contributed to the continuous oxygen and thermal stratification during this time compared to the intermittent condition occurring from June 2009 through March 2010. Wind conditions (not measured) may have also differed between these contrasting periods of oxygen stratification.

Intermittent stratification reflecting a polymictic condition is likely common for the types of basins occurring in southwest Florida. Conducting vertical D.O. and temperature profiles only once per summer would not adequately characterize a seasonal polymictic condition as was evident from the continuous monitoring at Site 8. An additional profile measured during July 2007 at Site 11 resulted in an oxygen stratified profile as compared to the unstratified condition occurring six days previously, again suggesting a variable frequency and duration period of oxygen stratification (Fig. 15).

Relatively deep basins (avg. max. depth 7.8-8.6 m) closest to the coast (Sites 8, 9 and 10) had distinct D.O. vertical points of inflection that coincided with an abrupt increase in specific conductance (Figures 11 and 12 illustrated for Site 8 only). We interpret this as an indication of saline groundwater intrusion from proximal coastal waters. It's probable that groundwater higher in conductivity is more mineralized and denser and may resist vertical mixing leading to or facilitating a hypoxic bottom layer. This same condition was not seen in near coastal sites 1, 3 and 4 that were relatively shallow with average maximum depths of 2.4-5.0 m. A relatively deep inland basin (Site 11) with an average maximum depth of 8.5 m, did not demonstrate this sharp inverse coincidental relationship with D.O. and specific conductance in a vertical context.

The morphometric parameters that best explained variability of bottom D.O. were maximum depth, average depth and surface to volume ratio (Figures 17, 16 and 18 respectively). Other parameters measured that have implications for vertical mixing such as Relative Depth Z_r , dynamic ratio and fetch distance were less predictable indicators of bottom hypoxia (Figures 20, 22 and 21 respectively). However, fetch distance did demonstrate a significant ($p \leq 0.05$) positive relationship with maximum depth (Fig. 23) and may explain why some of the deepest basins demonstrated an infrequent or an indistinct hypoxic layer. The Trophic State Index (a relative measure of nutrient enrichment) was a poor indicator of hypoxia in the basins studied.

Summary

- Many artificial basins in coastal southwest Florida develop a hypoxic bottom layer for various durations and occurrences during the year. The duration of an oxygen stratified condition leading to a bottom hypoxic layer can have implications for depressing whole water column D.O. concentrations often causing fish mortality at the time of destratification and for mobilization of nutrients from the sediments to the water column.
- Thermal stratification was only detected at one of the deepest basins and it appears that a bottom hypoxic layer can form independent of thermal stratification likely resulting from bacterial respiration in the sediments and the upwelling influence of saline groundwater that may inhibit mixing.
- Hypoxia in artificial basins in southwest Florida can be characterized three ways as a component of the vertical water column strata. These include 1) a distinct bottom layer defined by an abrupt vertical change in D.O. concentration where the ambient condition remains hypoxic; 2) a weak or indistinct layer with minor reductions in D.O. concentration with increasing depth; 3) no oxygen stratification. There is likely little seasonal effect on whole water column D.O. concentration where the hypoxic layer is weakly defined and relatively minor in degree. This condition of minor vertical change in D.O. along with the two sites that did not exhibit oxygen stratification, defined approximately half of the basins studied here.

- A hypoxic bottom layer particularly in relatively deep basins (e.g. maximum depth > 6 m) was found to occur every month, February through November. This hypoxic strata can last for as little as several days or a week and occur intermittently during the year or last continuously during the warmer months of March through September depending on multiple variables such as climate, basin morphometry, speed and duration of wind, and proximity to saline coastal waters as they may influence the nature of groundwater upwelling to the artificial basin in question.
- Intermittent vertical mixing that often results in oxygen stratification between mixing events and the formation of a relatively brief bottom hypoxic layer, may be the most common pattern for artificial ponds constructed in coastal southwest Florida. This pattern is likely influenced by a higher vulnerability to changes in wind stress and changes in heat content leading to low maximum stability similar to tropical lakes.
- Relatively deep basins proximal to coastal saline waters may be influenced to a greater degree by saline and highly mineralized groundwater that may promote a density gradient and inhibit vertical mixing and facilitate the formation of a bottom hypoxic layer.
- The morphometric basin parameters that best explained the variation in hypoxia were maximum depth, surface to volume ratio and average depth. To minimize the frequency and duration of a hypoxic bottom layer, artificial basins should be constructed to not exceed 3.6 m average depth (Fig. 16) and five meters maximum depth (Fig. 17). The surface to volume ratio as calculated here should exceed 0.1 (Fig. 18), again to maximize mixing depth.

Literature Cited

- Bachmann, R.W., M.V. Hoyer, and D.E. Canfield, Jr. 2000. The potential for wave disturbance in shallow Florida lakes. *Lake and Reserv. Manage.* 16(4):281-291.
- Lewis, M.L., Jr. 1987. Tropical limnology. *Ann. Rev. Ecol. Syst.* 18:159-184.
- Sperling, E. V. 1998. Role of relative depth in the prediction of eutrophication of lakes and reservoirs. In: *Asociación Peruana de IngenierÍA Sanitaria y Ambiental; AIDIS. Gestión ambiental en el siglo XXI.* Lima, APIS, 1998. p.1-4.
- Weyhenmeyer, G.A. and J. Bloesch. 2001. The pattern of particle flux variability in Swedish and Swiss lakes. *Science of the Total Environment* 266:69-78.
- Wetzel, R.G. and G.E. Likens. 1991. *Limnological Analyses*. 2nd ed. Springer.