Mirror Lake
Tuftonboro, New Hampshire

Internal Phosphorus Loading and Cyanobacteria Response

NEW HAMPSHIRE DEPARTMENT OF Environmental Services

2011

DES-R-WD-11-19

Mirror Lake
Internal Phosphorus Loading
and Cyanobacteria Response

Final Report
2011

New Hampshire Department of Environmental Services

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ACKNOWLEDGMENTS

The authors wish to acknowledge the Biology Section Staff of the Department of Environmental Services for their professional assistance in the field and laboratory. Particular thanks goes to Biology Intern Josh Connor for providing endless support during the sampling season, Biology Intern Sarah Pease for thoroughly reviewing this document and Biology Staff Walter Henderson, Amy Smagula and Scott Ashley for analyzing samples and lending an extra set of hands when needed during the field season.

The efforts of Rachel Rainey and support staff of the DES Laboratory in coordinating and processing the chemical analyses for the study are greatly appreciated.

Robert Hartzel and Chad Yaindl, GeoSyntec Consultants, are also acknowledged for their assistance in providing annual watershed phosphorus load estimates and professional expertise on generating accurate in-lake modeling outputs.

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1.0 INTRODUCTION AND PURPOSE

1.1 Introduction

Mirror Lake is located in the Lakes Region of New Hampshire. The 378 acre lake, located primarily in Tuftonboro, has a relatively small 1,792 acre watershed (Appendix A) within Tuftonboro (population 2,148; U.S. Census 2000) and neighboring Wolfeboro (population 6,083; U.S. Census 2000). With an average depth of 4 meters, Mirror Lake consists of a single basin with a maximum depth of 13.1 meters. The Mirror Lake Protective Association has been monitoring lake water quality through the University of New Hampshire's Center of Freshwater Biology Lakes Lay Monitoring Program since 1991.

The presence of cyanobacteria surface scums is documented by DES Beach Program personnel during the swimming season (June through August) or when there are lakeshore owner complaints. In Mirror Lake, cyanobacteria surface scums often occur in late summer and early fall, although cyanobacteria cell migration occurs through the water column throughout July to mid-October. DES biologists documented cyanobacteria blooms or surface scums on September 16, 2008 and September 2, 2010.

Mirror Lake, used mostly by lake residents and transient boaters and fisherman, was designated in the 2008 Federal Section 303(d) list as a waterbody impaired for "primary contact recreation"--a result of reoccurring cyanobacteria surface scums. Mirror Lake was not listed on the 303(d) list for the "aquatic life use" (ALU) impairment in 2010, since the 10 year median Total Phosphorus (TP) was 8.0 ug/L and chlorophyll-a (Chl-a) value was 2.7 ug/L and therefore well within or better than the criteria for mesotrophic lakes (data sources included UNH and DES). Median epilimnetic TP and Chl-a (6 meter composite) values collected by DES from May 24 through September 15, 2010 were 9.25 ug/L and 4.55 ug/L, respectively, also within the ALU criteria mesotrophic range. See Appendix B for a summary of the State's Consolidated Assessment Listing Methodology and Section 303(d)/ 305(b) reporting.

The impaired waterbody designation resulted in a DES funded EPA Section 319 NPS restoration grant to develop a watershed management plan (WMP). The Mirror Lake Watershed Management Plan, anticipated for release this year, will assist with watershed planning and outline potential best management practices to reduce phosphorus (P) loading to Mirror Lake. The WMP goals will likely include reducing cyanobacteria cell production, increasing lake clarity and increasing recreational use days. The decrease in cyanobacteria cell production and cyanotoxicity can only be achieved through phosphorus load reductions to the lake from watershed and internal P loading. Outlining a strategy to manage or control cyanobacteria cell production is an extremely difficult task. An actual in-lake phosphorus threshold concentration that limits cyanobacteria cell production has not been determined through limnological research. However, it is well documented that increased P and nitrogen (N) loading results in subsequent increases to in-lake phosphorus concentration and primary productivity. Furthermore, freshwater systems having molar ratios of total N to total P that are less than 15 become nitrogen limited and are more likely to experience cyanobacteria dominance (Smith 1983, 1990).

Phosphorus loading reductions through watershed management and hypolimnetic phosphorus inactivation were successful at Kezar Lake in North Sutton, New Hampshire

(Connor and Martin 1989). This lake restoration project effectively demonstrated that substantial chlorophyll reductions, increased lake clarity, and elimination of cyanobacteria dominance to a natural succession of phytoplankton species can occur following watershed phosphorus loading reductions and properly researched and implemented in-lake restorative efforts. Although Mirror Lake is not currently impaired for Chl-a, P load reductions both from the watershed and internally from the lake would likely lower the Chl-a concentration through a reduction of phytoplankton and cyanobacteria cell production.

Although cyanobacteria blooms are often documented in late summer and fall as the cells rise to the surface, cell densities have periodically been documented by DES biologists at monitored lake depths since 1992 (New Hampshire Department of Environmental Services, 1994). Cyanobacteria cell densities and other data show that lake temperature and hypolimnetic anoxia increase with summer progression, leading to internal phosphorus loading. Because of the simultaneous release and uptake within the sediments, documentation of internal P load rates can only be estimated through mass balance equations. Limnological studies have shown phosphorus entrainment through stratified lakes, phosphorus mixing in weakly stratified lakes and total phosphorus mixing during fall turnover. It is likely that the high hypolimnetic phosphorus load does impact Mirror Lake's water quality. Estimating the internal P load and cyanobacteria response will provide a better understanding of the impacts of internal P loading on Mirror Lake for inclusion in the Mirror Lake Watershed Management Plan.

Several in-lake Water Quality Models (Vollenweider 1976; Chapra 1975; Dillon and Rigler 1974; Kirchner and Dillon 1975; Larsen and Mercier 1976; Jones and Bachmann 1976) may be utilized in the WMP to predict the influence of watershed phosphorus loading on lake quality. These models predict in-lake phosphorus concentration based on phosphorus loads from the watershed following spring overturn, during fully-mixed conditions. These models place little emphasis on internal phosphorus loads, which can have a substantial impact on water quality, causing increased primary productivity and cyanobacteria blooms. As a result, several Nürnberg Models (1998) that account for internal P loads will also be evaluated. Only through continued research will limnologists fully understand the role of internal P loading and how it influences cyanobacteria and subsequent scum formation.

1.2 Purpose

The purpose of this Mirror Lake study was to:

1) Monitor the fully-mixed, spring and fall in-lake phosphorus conditions

2) Measure in-lake temperature, dissolved oxygen (DO), specific conductance, turbidity, pH and chlorophyll-a after the spring turnover through summer and fall until the fall turnover

3) Measure internal P loading after the spring turnover through summer and fall until the fall turnover

4) Measure internal P loading prior to cyanobacteria dominance of the phytoplankton (as measured by relative abundance)

The above information was then applied to in-lake phosphorus models to determine the internal P load impact on in-lake P concentrations and determine the P load reductions necessary to prevent increased algal and cyanobacteria cell production. These elements will be addressed in the Mirror Lake Watershed Management Plan.

2.0 METHODOLOGY

Weekly in-lake data was collected for the following lake quality parameters:

1) Temperature, dissolved oxygen (DO), specific conductance, turbidity, pH and chlorophyll-a. The deep spot depth profile was measured for the above listed parameters using a Hydrolab DataSonde 5 at intervals ranging from 0.1 to 0.5 meters. Each recorded measurement was a five-measurement average.

2) Chlorophyll-a, composite sample. Surface to mid-metalimnion or slightly deeper if Chl-a was evident below the mid-metalimnion based on data collected during the depth profile.

3) Plankton haul (80 micron net) sample to determine plankton relative abundances. Two samples were collected; one corresponding with the Chl-a sample depth (0-6 meters) and one with lake bottom depth (0-12 meters).

4) Discrete Total Phosphorus (P) samples taken at 3 meters, to represent epilimnetic and metalimnetic P concentrations, and at 11 meters, to represent hypolimnetic P concentration.

5) Secchi disk depth to measure lake clarity.

Additional nutrient sample collection included a P profile in April and October, 2010 and a P and dissolved ortho-phosphorus (DOP) profile in August, 2010.

Additional phytoplankton sample collection included meter interval discriminate plankton hauls in August, 2010.

3.0 STUDY DATA

In-lake data was collected beginning during the spring turnover in early April, 2010 and weekly from late May until the fall turnover in mid-October, 2010. The following sections discuss data collected for temperature and dissolved oxygen profiles, phosphorus, turbidity and chlorophyll-a profiles, secchi depth and relative plankton abundance.

3.1 Temperature/ Dissolved Oxygen

Temperature/DO or Temperature/LDO profiles were collected April 8 and weekly from May 27 through October 13. Figure 3-1, demonstrates that the lake was thermally destratified when water temperatures measured were between 6ºC and 12ºC. Oxygen concentrations were greater than 10 mg/l, or 90 percent saturation, throughout the April profile. Thermal stratification of the lake was documented by May 27 as seen in Figure 3-2. Hypolimnetic dissolved oxygen concentration gradually decreased throughout the month of June from approximately 15 percent to 9 percent in the bottom half meter.

Starting July 1 and continuing through August 19, a low hypolimnetic dissolved oxygen concentration area (less than 3 percent saturation) expanded. By early July, low dissolved oxygen concentrations were measured in the bottom 0.8 meters. Low dissolved oxygen concentrations were measured in late August within the bottom 4.8 (8.8-13.5 meter depth) to 5.8 (6.7-12.5 meter depth) meters with the occasional exception of a dissolved oxygen increase or spike due to increased algal productivity around 7.5 meters. See Figures 3-3 through 3-6 for dissolved oxygen percent saturation profiles. Starting in mid-September, temperature stratification began to weaken, with thermal conditions present by October 13; this is shown in Figures 3-7 and 3-8.

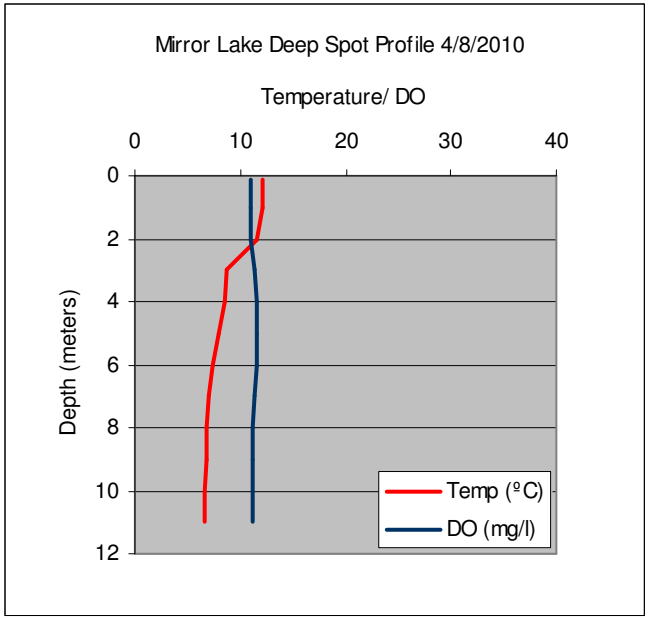

Figure 3-1: Temp/ DO profile, April 8

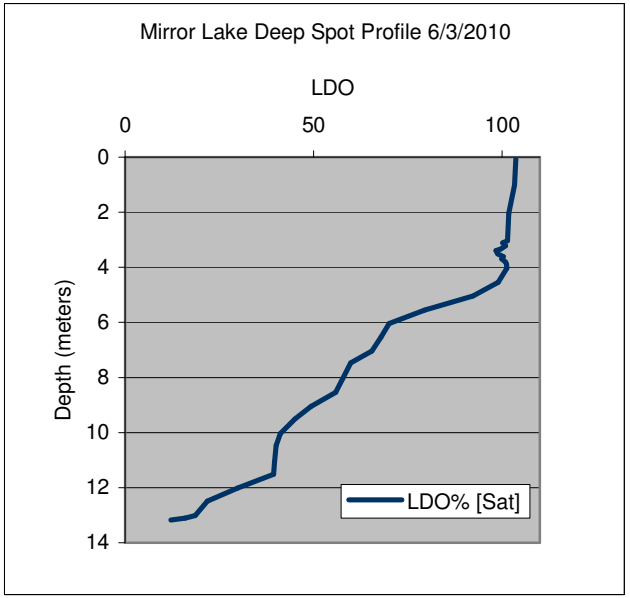

Figure 3-3: LDO profile, June 3

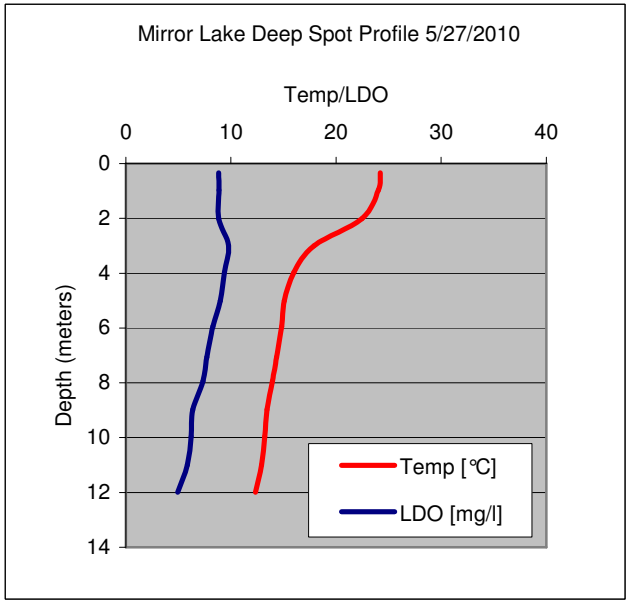

Figure 3-2: Temp/ LDO profile, May 27

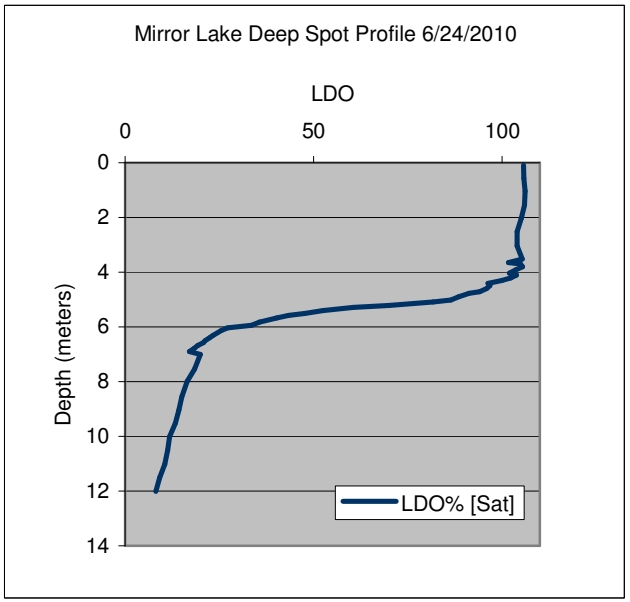

Figure 3-4: LDO profile, June 24

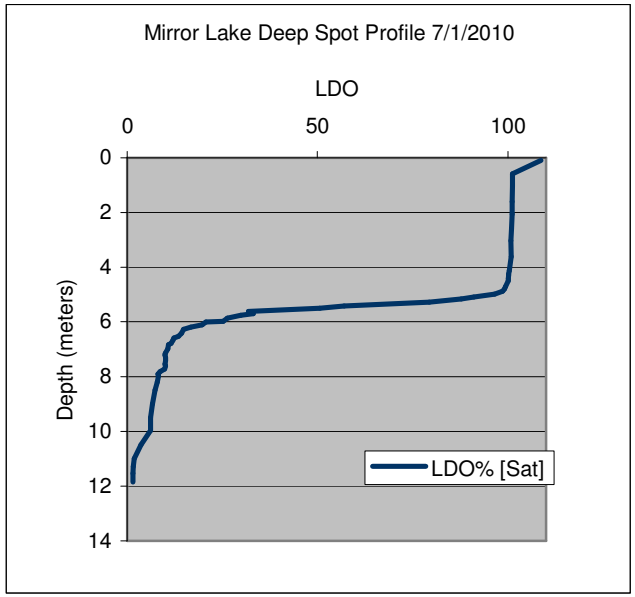

Figure 3-5: LDO profile, July 1

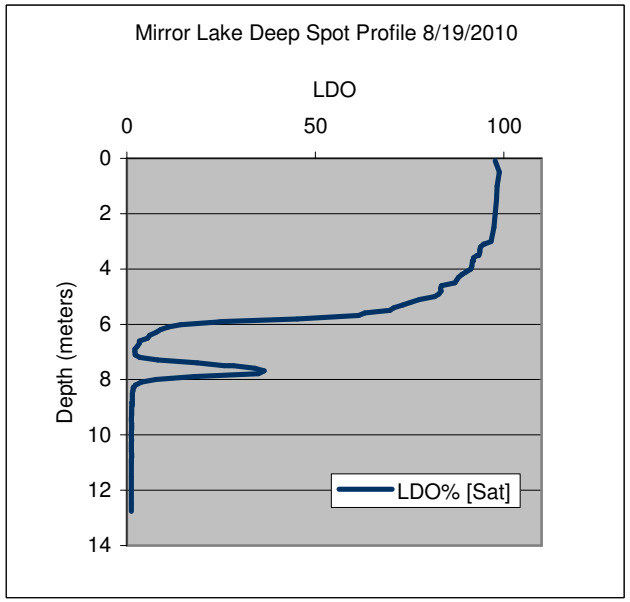

Figure 3-6: LDO profile, August 19

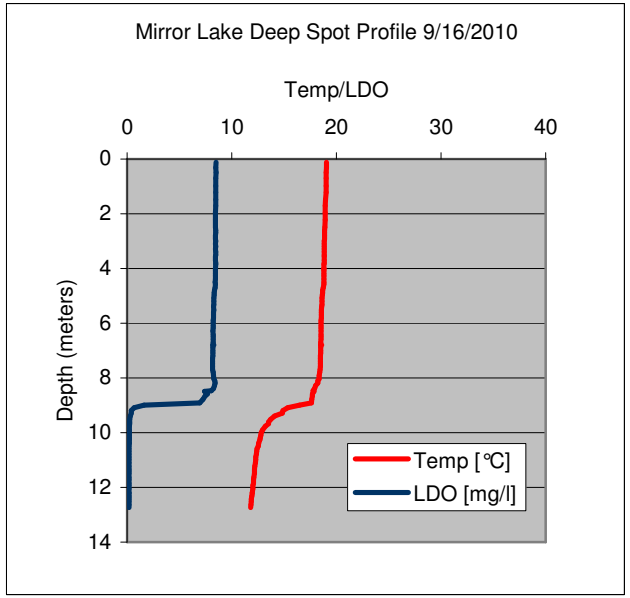

Figure 3-7: Temp/ LDO profile, September 16

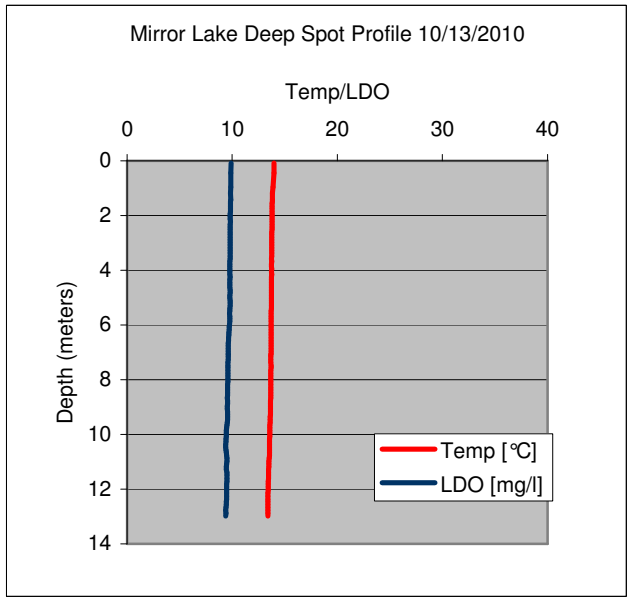

Figure 3-8: Temp/ LDO profile, October 13

3.2 Phosphorus

Total Phosphorus samples were collected on the dates and depths provided in Table 3-1.

Table 3-1: P Sample Dates and Depths

Date	Depth (meters)
April 8, 2010	1, 3, 7, 10
May 27, 2010	0.1, 2, 4, 6, 8, 10, 12, 13
September 16, 2010	0.5, 2, 4, 6, 8, 10, 12
October 13, 2010	1, 3, 7, 10
Weekly, June 3- October 13, 2010	3 (epilimnion) and 11 (hypolimnion)

The total lake volume, based on DES Lake Survey historical bathymetry, was estimated at approximately 6,185,000 cubic meters. In 2010, Mirror Lake bathymetry was reassessed. GPS was used to map 0.5 meter contours (Appendix C) for lake depths and to determine volumetric data for each half meter interval. The revised volume for Mirror Lake was 5,590,719 cubic meters.

Two methodologies, comparing whole water in-situ summer P increases were used to estimate internal P loading. These included measuring: 1) weekly in-situ summer P increases using P concentration data from the epilimnion and hypolimnion only and 2) in-situ summer P increases using P concentration profile data comparing maximum summer whole water column P mass in early September with that at the beginning of the summer period in late June, prior to summer internal P loading.

Internal P loading, weekly in-situ summer P increase comparison

Internal P loads can easily be calculated for anoxic lakes where anoxia is fully contained in the hypolimnion. Assuming uniform hypolimnetic P concentrations, simply multiply the hypolimnetic P concentration by the hypolimnetic lake volume. However, in Mirror Lake, anoxic conditions are present in the metalimnion from mid-August through September as the lake thermocline deepens during periods of warm summer temperatures. As a result, the hypolimnetic P mass does not remain in the hypolimnion and is instead transported physically as a result of thermocline deepening and biologically by algae and cyanobacteria at the hypolimnion-metalimnion interface and within the metalimnion.

To estimate the P load representative of internal P loading in Mirror Lake, P loads for the hypolimnion and the epilimnion/metalimnion must be calculated. Since metalimnetic P samples were not collected weekly, epilimnetic P samples were used to represent both metalimnetic and epilimnetic P. P mass values were extrapolated for each of the lake layers (hypolimnion and reduced volume epilimnion/metalimnion) by multiplying the P concentration by the associated depth volume; either the 0-9 meter depth volume directly over the 9 meter depth plane (Volume B), representing the

epilimnion and metalimnion, or 9-13.5 meter depth volume (Volume C) to represent the hypolimnion. To simplify the internal P load estimate, it was assumed that: 1) the epilimnetic/ metalimnetic volume that receives internal P loads is directly above where internal P loads are generated, 2) the anoxic hypolimnion is below 9 meters as derived from profile data and 3) that the internal P load transported to the epilimnion/metalimnion was evenly distributed throughout that volume. See Figure 3-9 for the Mirror Lake volume distribution used to calculate internal loading. Volume A is the remaining volume in the epilimnion and hypolimnion that is assumed to receive no internal P loads prior to destratification.

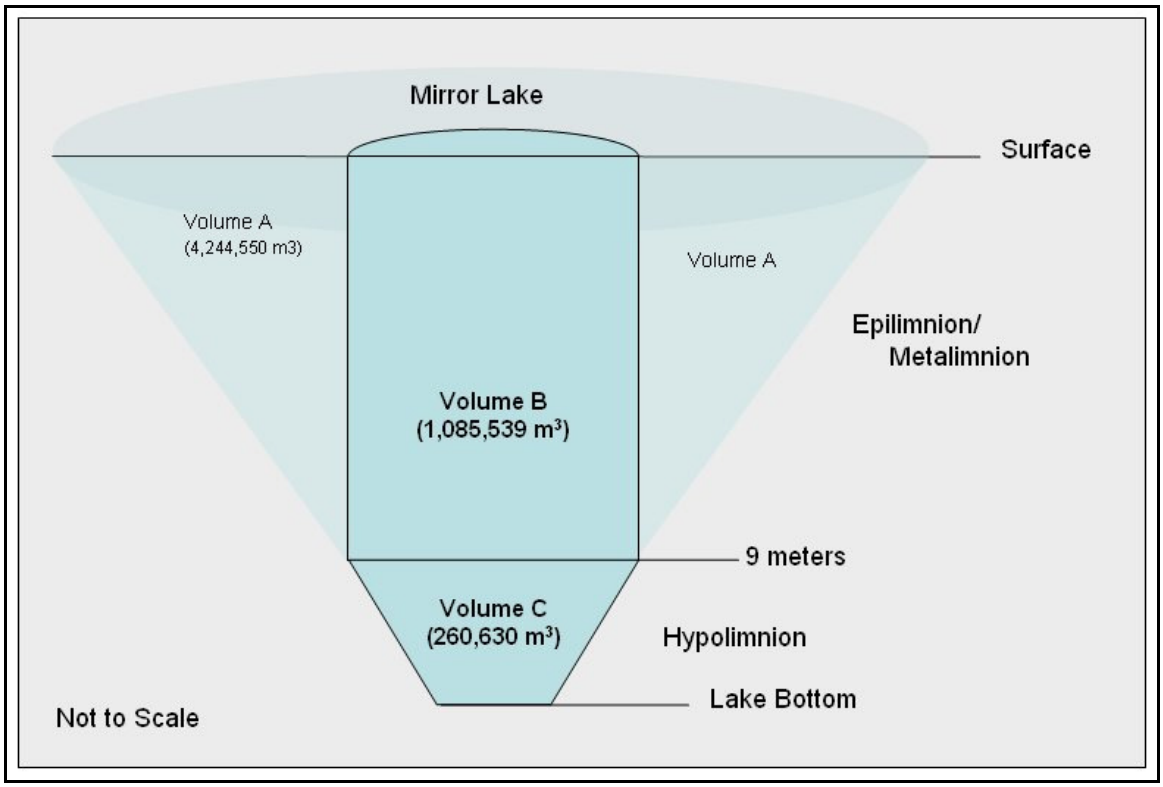

Figure 3-9: Mirror Lake Volume Distribution

To determine the P load representative of hypolimnetic internal P loading, a baseline P mass value prior to initiation of internal P loading in the hypolimnion was established. From May 27 through June 24, the hypolimnetic P mass ranged from 3.1 to 5.7 kg (Table 3-2). On June 24, the baseline hypolimnetic P mass equaled 5.2 kg. Any increase in hypolimnetic P mass after June 24 was considered a result of internal P loads. Internal P loading was due to a decrease in hypolimnetic oxygen below 2 percent and corresponding increase in hypolimnetic P concentration from 20 ug/l to 27 ug/l from June 24 to July 1.

To determine the P load representative of internal P loading in the epilimnion/metalimnion, a baseline P mass value for the epilimnion/metalimnion was established. On July 1, the baseline epilimnetic/metalimnetic P mass equaled 6.6 kg. Any increase in epilimnetic/metalimnetic P mass after July 8 was assumed to be due to internal P loads transported from the hypolimnion. This was supported by a P concentration increase in the deep spot epilimnion after July 8.

As the summer and anoxic conditions progressed, the P loads resulting from internal loading increased. On September 1, at the approximate height of internal P loading, a maximum internal P load of 30.9 kg existed in Mirror Lake. (See Appendices D and E.)

There are several shortcomings to this modeling approach. There is a lack of metalimnetic P data throughout the sampling season, site specific lake P data other than the deep spot and fluid dynamics modeling that would have yielded a better understanding of internal P load distribution throughout the lake system. In addition, variability in the predicted P mass and resulting load is dependent on the start and end dates selected for the model input based up P concentration trends. To reduce this variability, a trend line based upon the weekly data shown in Appendix E can be drawn representing the daily P mass increase in both the hypolimnion (6/24 – 9/1) and epilimnion/metalimnion (7/8 – 8/12 or 8/13 – 9/1); this also represents the internal P loads (Figure 3-10). If the slope of each trend line is multiplied by the number of internal P load days, [70 for the hypolimnion and 36 (7/8 – 8/12 time period) or 20 (8/13 – 9/1 time period) for the epilimnion/metalimnion] and summed, this variability is reduced. The resulting internal P load calculation is therefore reduced to 24.69 kg (Table 3-2).

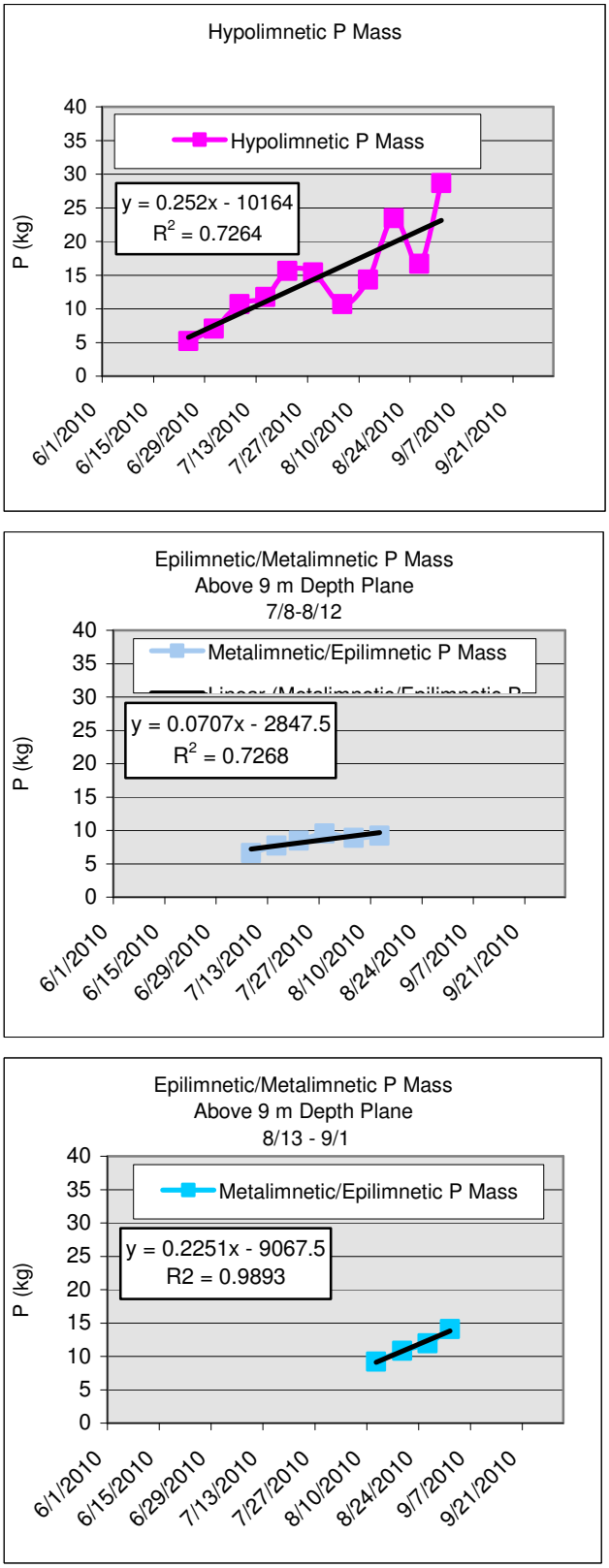

Figure 3-10: Hypolimnetic P Mass and Epilimnetic/Metalimnetic P Mass Trend Lines

Table 3-2: Weekly Internal P Load, Hypo. and Epi./Meta. Trend Line

	Trend Line Slope	Internal P Load Period	Internal P load Days	Internal P Load (kg)
Hypo.	0.2520	6/24-9/1	70	17.64
Meta./Epi.	0.0707	7/8-8/12	36	2.55
Meta./Epi.	0.2251	8/13-9/1	20	4.50
			Total Internal P Load	**24.69**

Internal P loading, late spring versus late summer in-situ comparison

A second methodology, late spring versus late summer in-situ comparison, was used to estimate P loads resulting from internal loading (Nürnberg 1987). To estimate internal P loads, maximum whole water column P mass during maximum anoxia in September was compared to whole water P mass in late May prior to internal P loading. For Mirror Lake, P profiles were collected on April 8 during spring, fully-mixed lake conditions; May 27, prior to internal loading; September 16, at the height of internal P loading and therefore the approximate maximum summer whole water P mass; and October 13, during fall, fully-mixed lake conditions. Whole water P mass estimates were determined by multiplying concentrations by volumes. Volumes were first calculated as they were in Figure 3-9, with the exception that the water column volume directly above the 9 meter depth plane was further divided based upon P sample collection on that date (Figure 3-11). The resulting whole water P mass difference from May to September resulting from internal P loading was 6.2 kg (Table 3-3). However, a whole water P mass difference of 6.2 kg likely underestimates the internal P load as it only captures the internal P load that is transported from the hypolimnion vertically throughout the lake, ignoring any lateral transport from the hypolimnion.

To account for the P load transported laterally, it was assumed that the majority of the lateral transport would occur in the metalimnion, where the P could be assimilated by algae. The epilimnion/metalimnion interface on September 16 was approximately 3.5 meters. The model showed that if laterally-mixed conditions occurred within each lake layer as depicted in Figure 3-12 from approximately 3.5 meters to the bottom, that 15.6 kg of the 82.4 kg total lake P mass resulted from internal P loading when compared to the May 27 whole water P mass estimate (66.8 kg P) as shown in Table 3-4.

As with the previous models, there are shortcomings to this modeling approach, including a lack of P data within other parts of the lake to verify the extent of lateral P transport or increased fluid dynamics modeling. Having additional P data and fluid dynamics modeling would have yielded a better understanding of the distribution of internal P loads throughout the lake system.

The internal P load models provided outputs that suggest the internal summer P load for Mirror Lake in 2010 fell between 6.2 kg and 24.69 kg. Recognizing there will be output variability with any model, the weekly in-situ summer P increase comparison (24.69 kg P) was considered to yield the most robust model output since this methodology accounted for more detailed, weekly P load assessments. As a result, this value will be applied to Section 4.0 of this report.

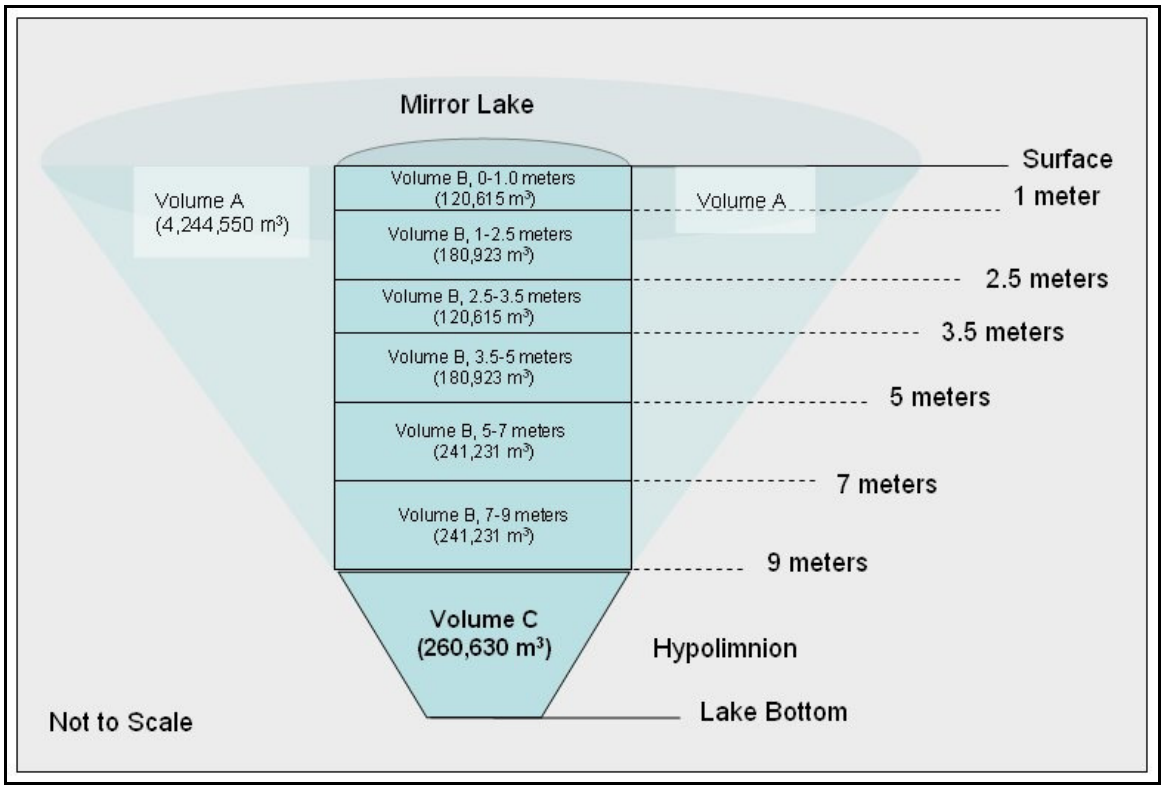

Figure 3-11: Mirror Lake Volume Distribution, September 16: Vertical P Transport

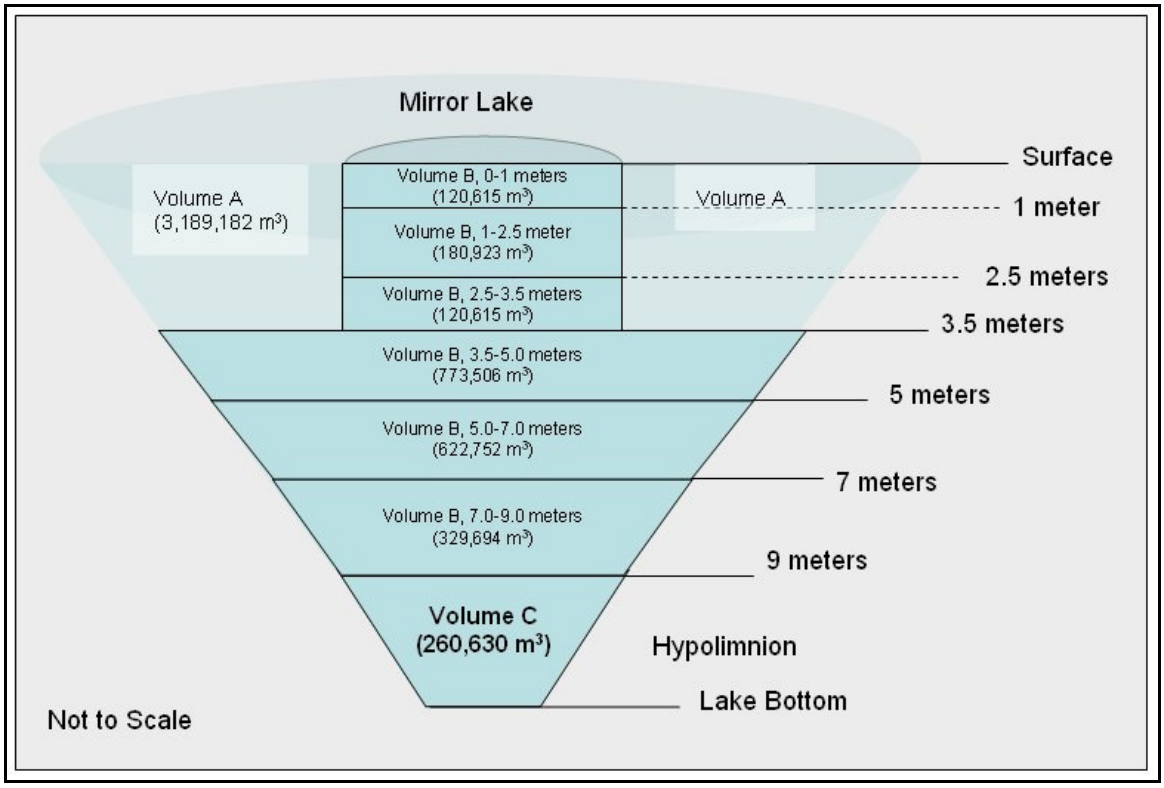

Figure 3-12: Mirror Lake Volume Distribution, September 16: Vertical and Horizontal P Transport

Table 3-3: Mirror Lake Phosphorus Whole Water Profiles with Vertical P Transport

4/8/2010						
Depth (m)	TP (ug/l)		Volume (l)		Mass (kg)	Volume-Weighted Avg. P (ug/l)
1.00	12.0		2341204229		28.1	
3.00	10.0		2036438871		20.4	
7.00	9.7		887796578		8.6	
10.00	9.8		325280846		3.2	
Total			**5590720523**		**60.3**	0.0108
5/27/2010						
Depth (m)	TP (ug/l)		Volume (l)		Mass (kg)	Volume-Weighted Avg. P (ug/l)
0.100	11.0		1256165093		13.8	
2.000	12.0		2001673183		24.0	
4.000	11.0		1119804824		12.3	
6.000	15.0		622752132		9.3	
8.000	12.0		329694994		4.0	
10.000	12.0		184780700		2.2	
12.000	14.0		68278829		1.0	
13.000	18.0		7570768		0.1	
Total			**5590720523**		**66.8**	0.0119
9/16/2010						
Depth (m)	TP (ug/l) (Vol A)	TP (ug/l) (Vol B/C)	Volume A (l)	Volume B/C (l)	Mass (kg)	Volume-Weighted Avg. P (ug/l)
0.5	9.6	11.0	1135549548	120615545	12.2	
2.0	9.6	11.0	1389422858	180923317	15.3	
3.0	9.6	16.0	657009920	120615545	8.2	
4.0	9.6	24.0	592583049	180923317	10.0	
6.0	9.6	12.0	381521042	241231090	6.6	
8.0	9.6	10.0	88463904	241231090	3.3	
10.0	N/A	32.0	N/A	148422219	4.7	
11.0	N/A	92.0	N/A	66339157	6.1	
12.0	N/A	140.0	N/A	45868920	6.4	
Total			**5590720523**		**72.9**	0.0130
10/13/2010						
Depth	TP (mg/l)		Volume (l)		Mass (kg)	Volume-Weighted Avg. P (ug/l)
1.000	14.0		2341204229		32.8	
3.000	14.0		2036438871		28.5	
7.000	12.0		887796578		10.7	
10.000	12.0		279411926		3.4	
11.000	12.0		45868920		0.6	
Total			**5590720523**		**75.8**	0.0136
P Load increase from April 8 to May 27, 2010					**6.5**	
P Load increase from May 27 to September 16, 2010 (Internal P Load)					**6.2**	
P Load increase from September 16 to October 13, 2010					**2.9**	

Table 3-4: Mirror Lake Phosphorus Whole Water Profiles with Vertical and Horizontal P Transport

4/8/2010						
Depth (m)	TP (ug/l)		Volume (l)		Mass (kg)	Volume-Weighted Avg. P (ug/l)
1.00	12.0		2341204229		28.1	
3.00	10.0		2036438871		20.4	
7.00	9.7		887796578		8.6	
10.00	9.8		325280846		3.2	
Total			**5590720523**		**60.3**	0.0108
5/27/2010						
Depth (m)	TP (ug/l)		Volume (l)		Mass (kg)	Volume-Weighted Avg. P (ug/l)
0.100	11.0		1256165093		13.8	
2.000	12.0		2001673183		24.0	
4.000	11.0		1119804824		12.3	
6.000	15.0		622752132		9.3	
8.000	12.0		329694994		4.0	
10.000	12.0		184780700		2.2	
12.000	14.0		68278829		1.0	
13.000	18.0		7570768		0.1	
Total			**5590720523**		**66.8**	0.0119
9/16/2010						
Depth (m)	TP (ug/l) (Vol A)	TP (ug/l) (Vol B/C)	Volume A (l)	Volume B/C (l)	Mass (kg)	Volume-Weighted Avg. P (ug/l)
0.5	9.6	11.0	1135549548	120615545	12.2	
2.0	9.6	11.0	1389422858	180923317	15.3	
3.0	9.6	16.0	657009920	120615545	8.2	
4.0	N/A	24.0	N/A	773506366	18.6	
6.0	N/A	12.0	N/A	622752132	7.5	
8.0	N/A	10.0	N/A	329694994	3.3	
10.0	N/A	32.0	N/A	148422219	4.7	
11.0	N/A	92.0	N/A	66339157	6.1	
12.0	N/A	140.0	N/A	45868920	6.4	
Total			**5590720523**		**82.4**	0.0147
P Load increase from April 8 to May 27, 2010					**6.5**	
P Load increase from May 27 to September 16, 2010 (Internal P Load)					**15.6**	

3.3 Chlorophyll-a

Chlorophyll-a concentration is a measure of a green photosynthetic pigment present in phytoplankton and cyanobacteria cells. Measuring Chl-a, provides biologists with an indication of lake productivity through phytoplanktonic cellular concentration in the water column at any given time. Chl-a composite samples are typically collected as whole water samples from the water column where light-dependent algal productivity typically occurs (surface to the metalimnion). In addition to collecting Chl-a composite samples, for this study, Chl-a measurements were recorded from the surface to approximately 12 meters using a Hydrolab DS5 and Turner fluorescent chlorophyll-a sensor to develop Chl-a profiles. The collection of chlorophyll-a data identified potential cyanobacteria layers migrating from the hypolimnion to the metalimnion and epilimnion.

Maximum or peak Chl-a values varied throughout the 2010 summer season. Chl-a concentrations were less than 10 ug/l from late May to mid-June, 10 - 75 ug/l from mid-June to mid-August and less than 15 ug/l from mid-August to mid-October. Algal and/or cyanobacteria densities, as measured by chlorophyll-a concentration, were greatest within the metalimnion on most sampling events. Several sampling events revealed increased secondary Chl-a concentrations from mid-July through early September measured at the uppermost hypolimnetic section. The following profiles, Figures 3-13 through 3-32, show the progression of the Chl-a concentrations from May through October.

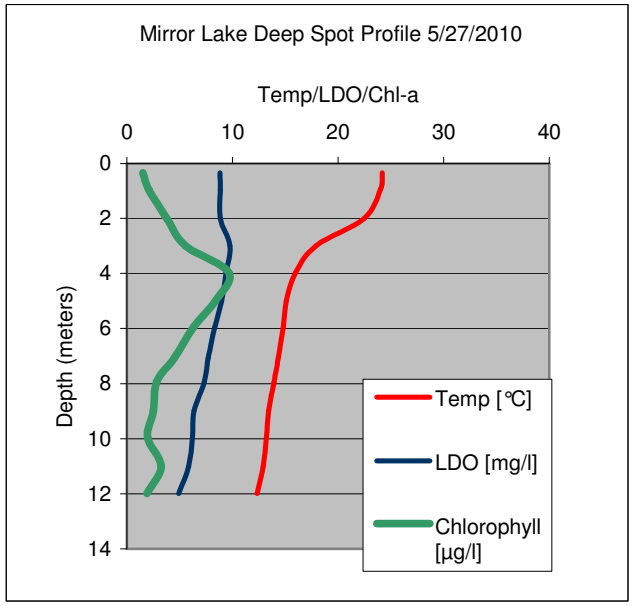

Figure 3-13: Temp/LDO/ Chl-a profile, May 27

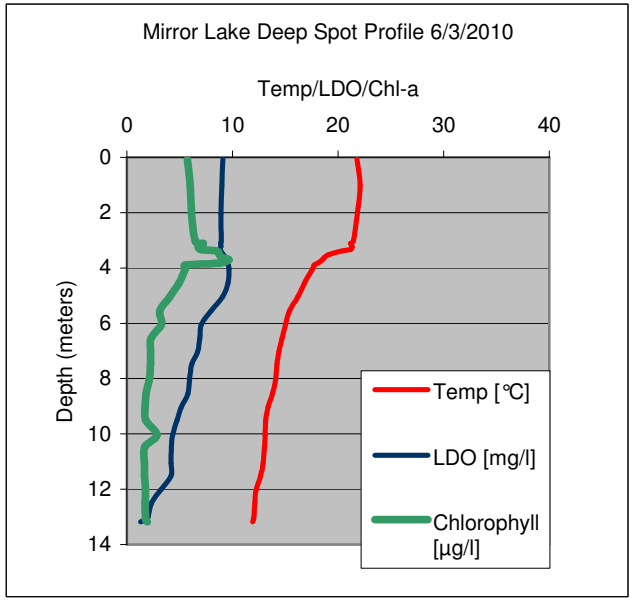

Figure 3-14: Temp/LDO/ Chl-a profile, June 3

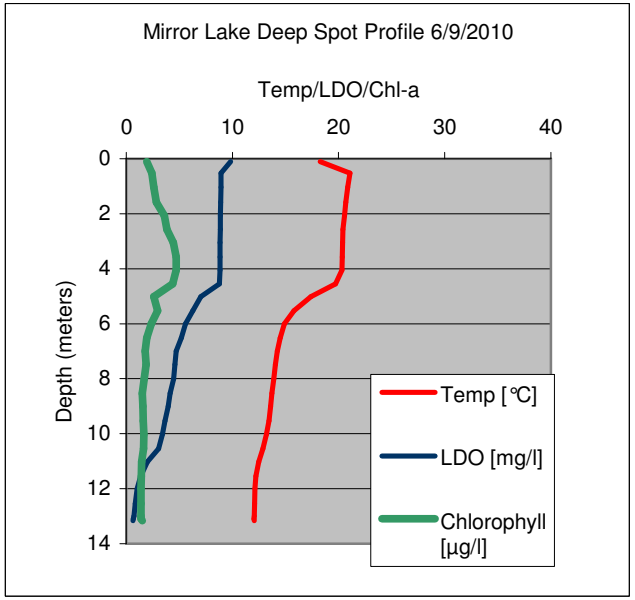

Figure 3-15: Temp/LDO/ Chl-a profile, June 9

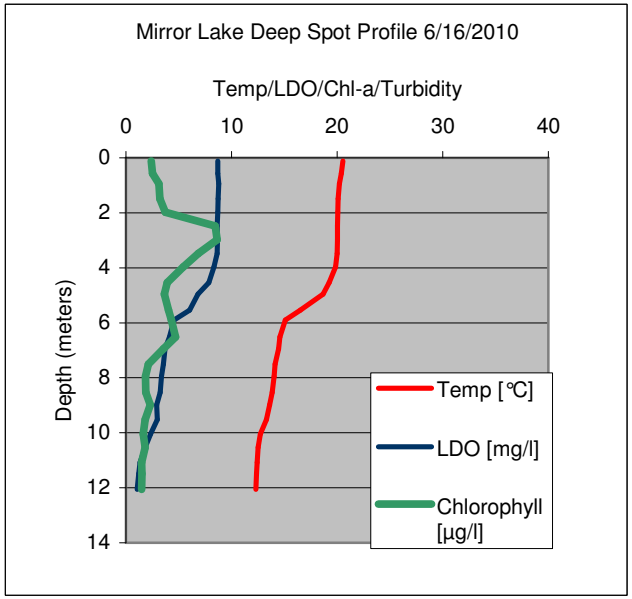

Figure 3-16: Temp/LDO/ Chl-a profile, June 16

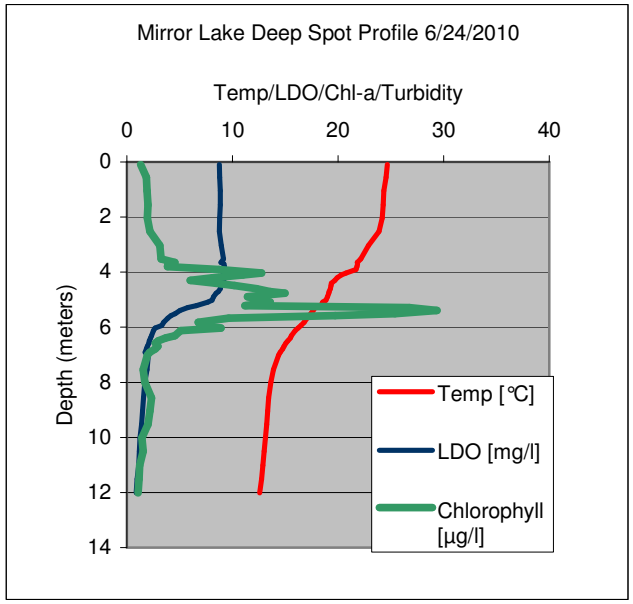

Figure 3-17: Temp/LDO/ Chl-a profile, June 24

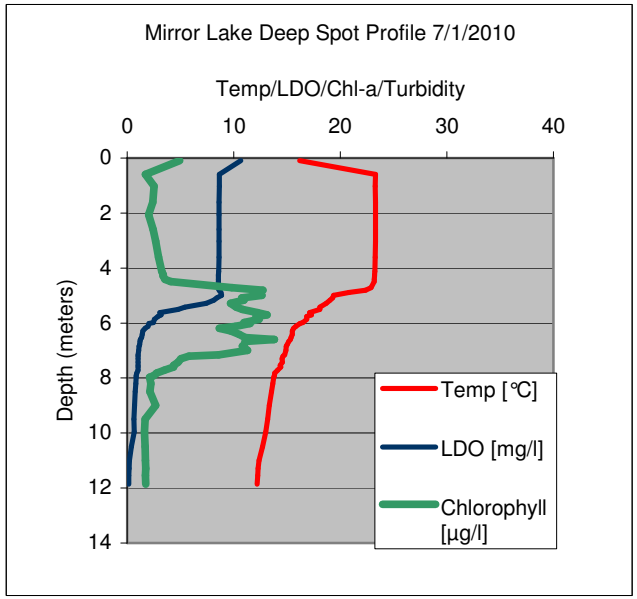

Figure 3-18: Temp/LDO/ Chl-a profile, July 1

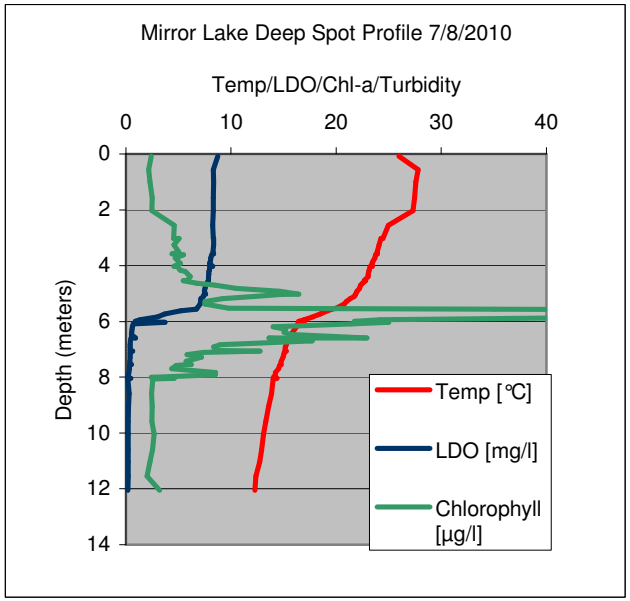

Figure 3-19: Temp/LDO/ Chl-a profile, July 8

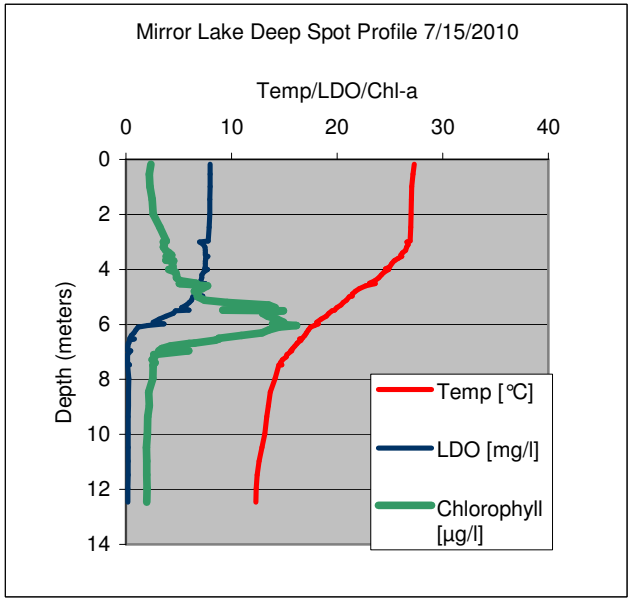

Figure 3-20: Temp/LDO/ Chl-a profile, July 15

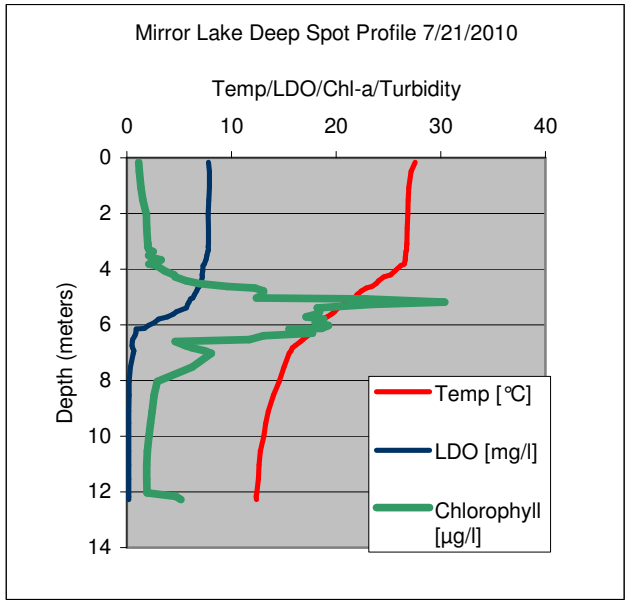

Figure 3-21: Temp/LDO/ Chl-a profile, July 21

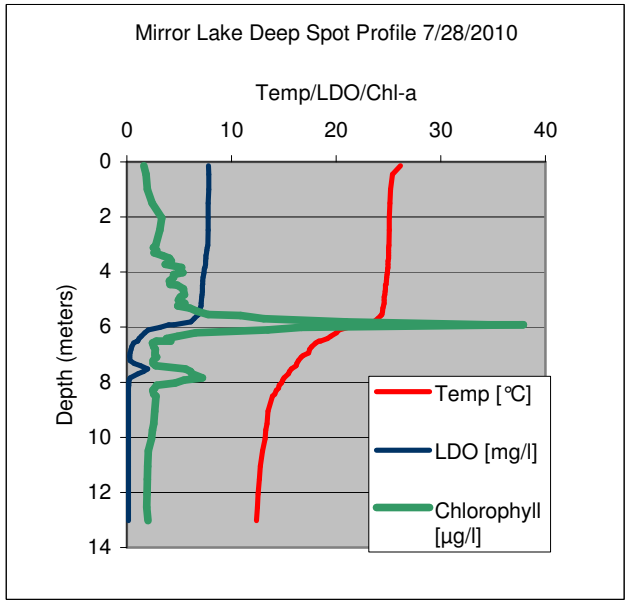

Figure 3-22: Temp/LDO/ Chl-a profile, July 28

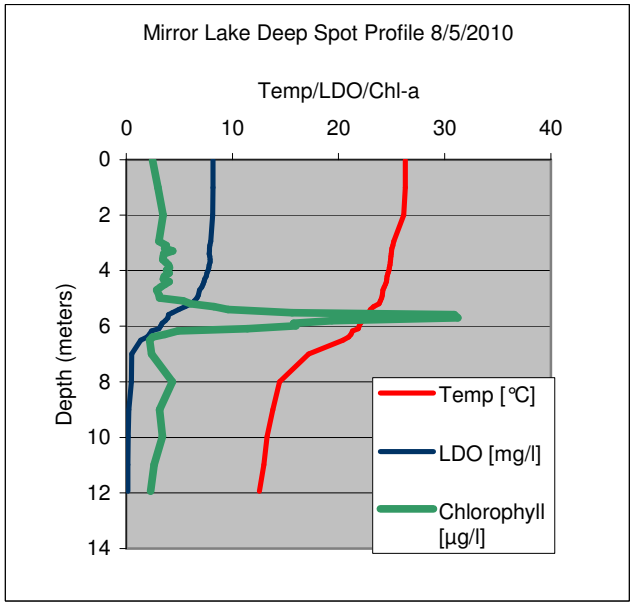

Figure 3-23: Temp/LDO/ Chl-a profile, August 5

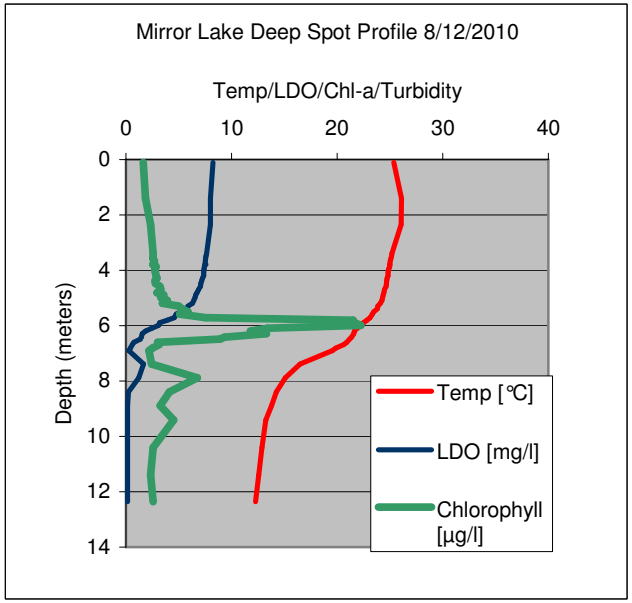

Figure 3-24: Temp/LDO/ Chl-a profile, August 12

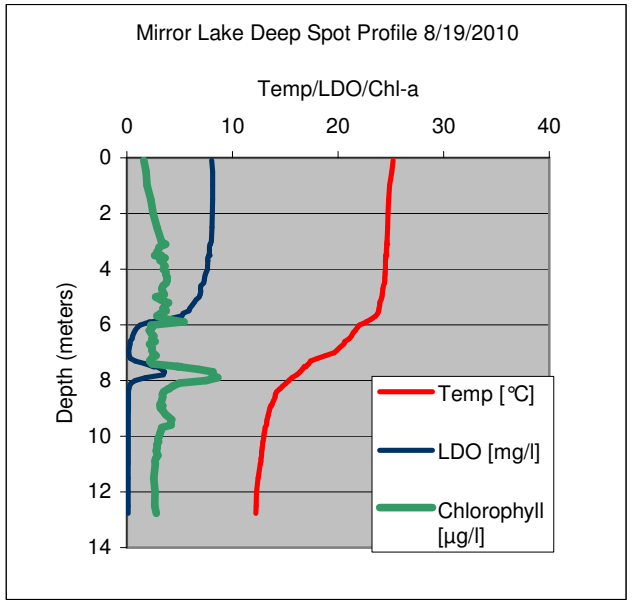

Figure 3-25: Temp/LDO/ Chl-a profile, August 19

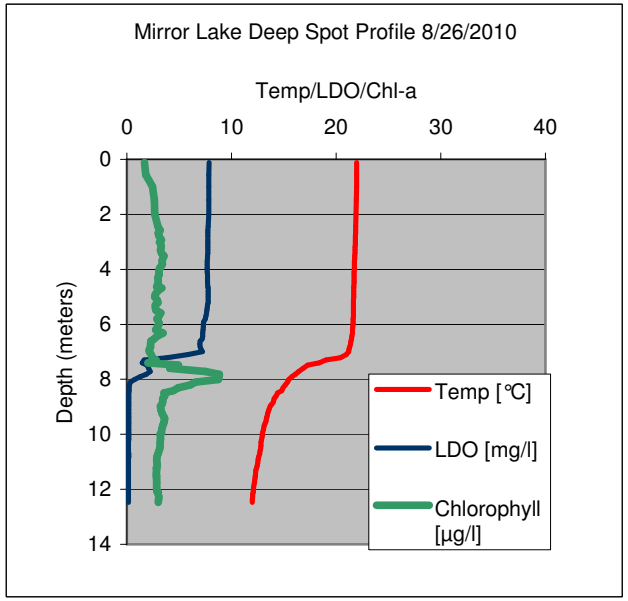

Figure 3-26: Temp/LDO/ Chl-a profile, August 26

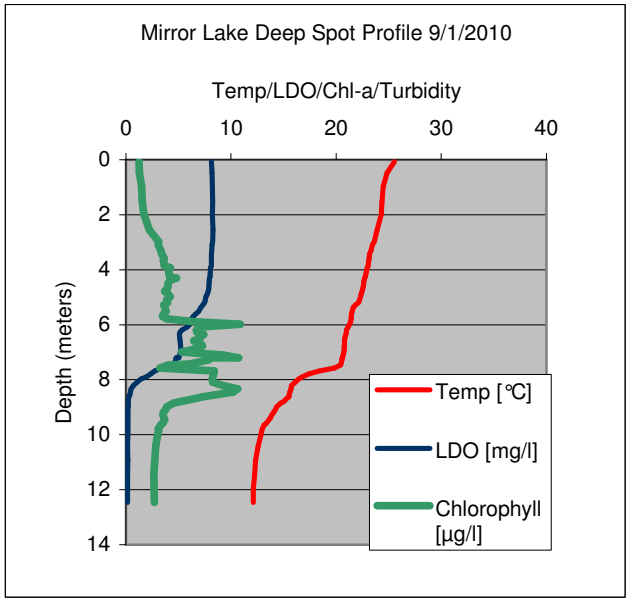

Figure 3-27: Temp/LDO/ Chl-a profile, September 1

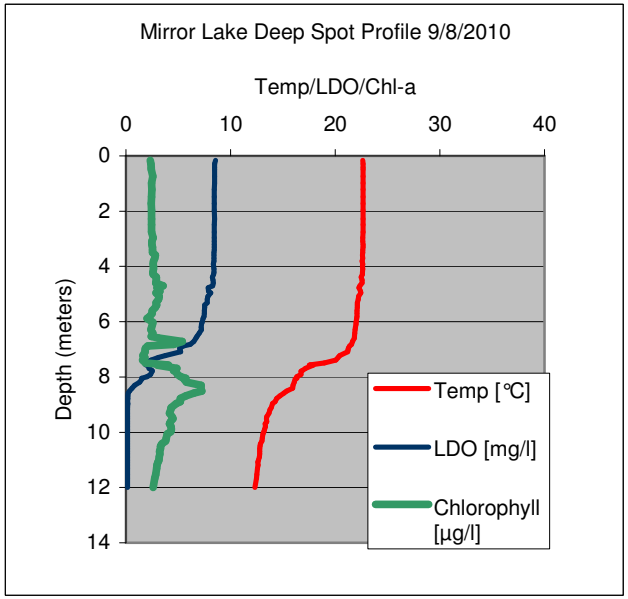

Figure 3-28: Temp/LDO/ Chl-a profile, September 8

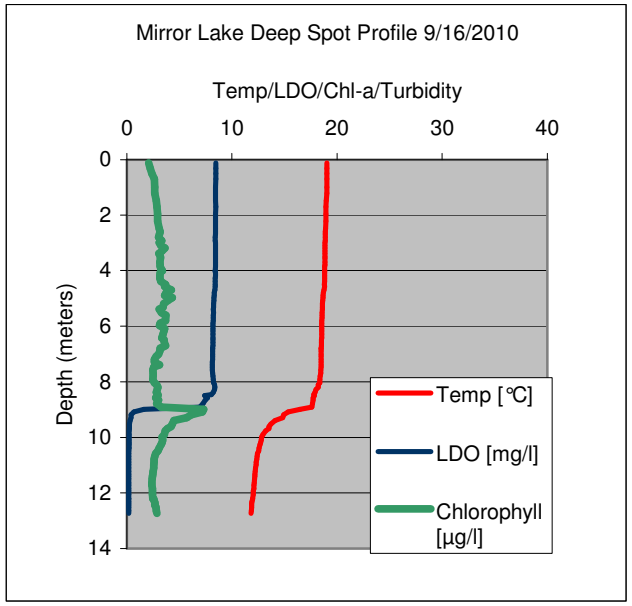

Figure 3-29: Temp/LDO/ Chl-a profile, September 16

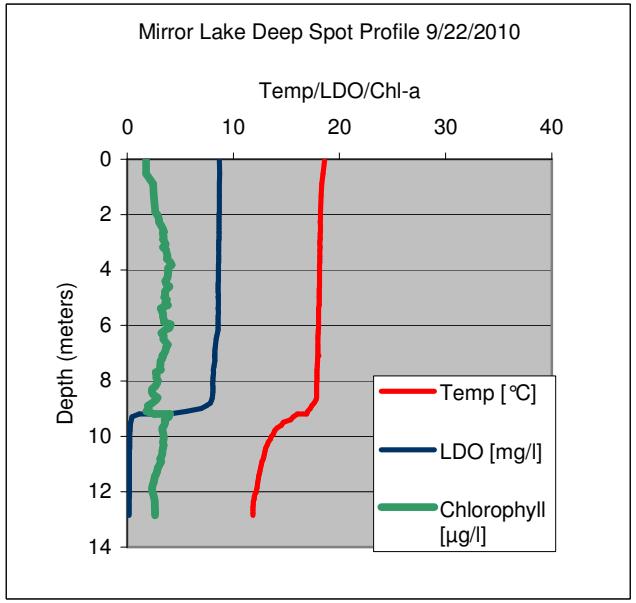

Figure 3-30: Temp/LDO/ Chl-a profile, September 22

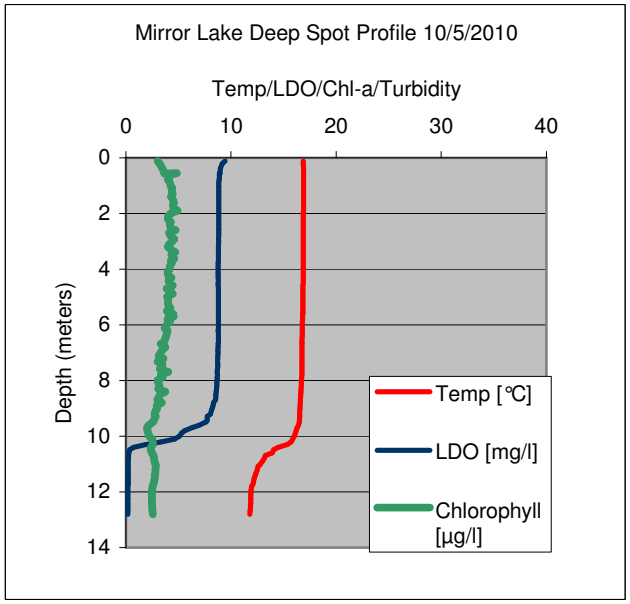

Figure 3-31: Temp/LDO/ Chl-a profile, October 5

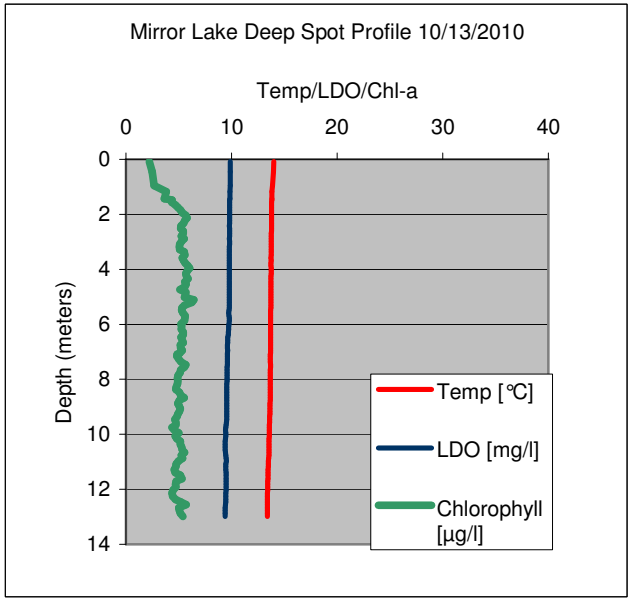

Figure 3-32: Temp/LDO/ Chl-a profile, October 13

3.4 Secchi Depth

Secchi depth measurements were recorded on a weekly basis from May through October (Figure 3-33). During the early summer months, end of May through early July, the secchi depth averaged 3.74 meters. Within two weeks of the onset of hypolimnetic internal loading, secchi depth increased, averaging 5.08 meters. This is most likely a result of a shift in algal productivity deeper in the water column, as seen in Figures 3-20 through 3-23. Secchi depth decreased slightly in early August to 4.43 meters, and decreased again to 3.70 meters in late August. The decrease in late August may be a result of significant rainfall in the previous 24 hours (1.63 inches, Manchester, NOAA), causing the transport of suspended solids into the lake, decreasing clarity. Secchi depth slightly increased to a mean depth of 4.69 meters during the month of September and again decreased to a mean depth of 4.00 meters in early October as the lake became fully-mixed during the fall turnover.

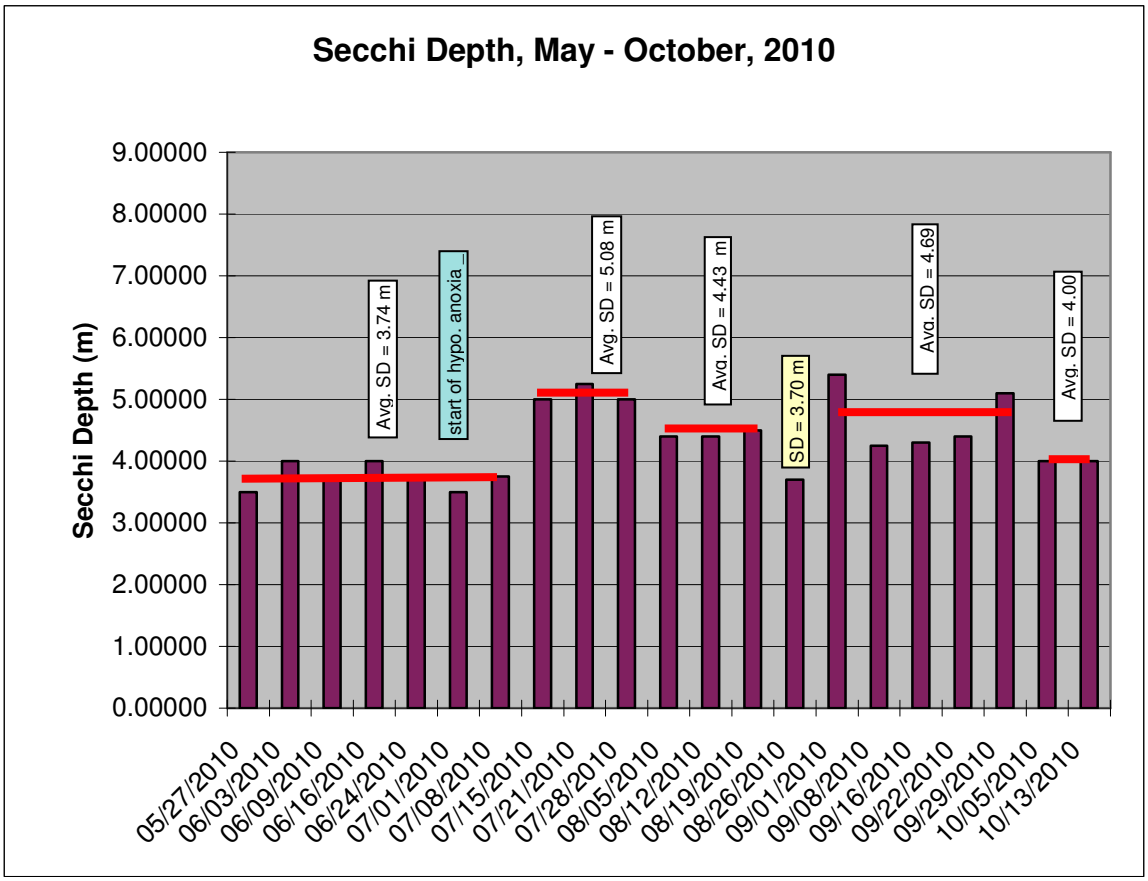

Figure 3-33: Mirror Lake Secchi Depth

3.5 Plankton

Three 80 micron plankton net samples were collected on a weekly basis from late May through early October; one mid-metalimnion vertical haul, one six meter vertical haul, and one full water column (0-13 +/- meter) vertical haul. Two taxonomic algal groups, [Chrysophyta (Golden-Brown) and Bacillariophyta (Diatoms)] and cyanobacteria dominated the Mirror Lake plankton community (full water column) at different times during the season. Golden-Brown, Diatom and cyanobacteria groupls often had relative abundances greater than 50 percent for extended periods of time during 2010. A third phytoplankton group, Pyrrophyta (Dinoflagellates) was present during most of the season but never attained whole water column relative abundance levels greater than 50 percent (Figure 3-34). However, Pyrrophyta did have relative abundances greater than 50 percent in the upper 6 meters during August (Figure 3-35).

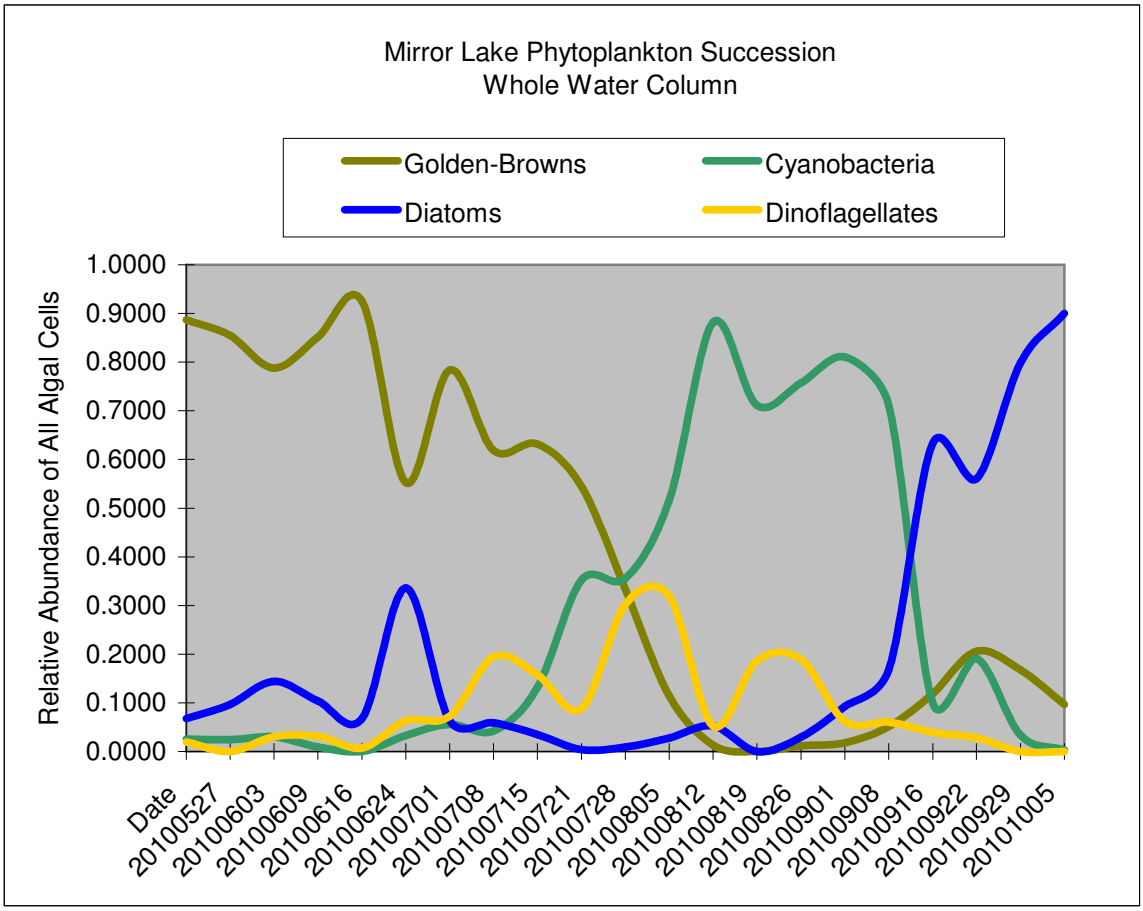

Figure 3-34: Mirror Lake Phytoplankton Succession, Whole Water Column

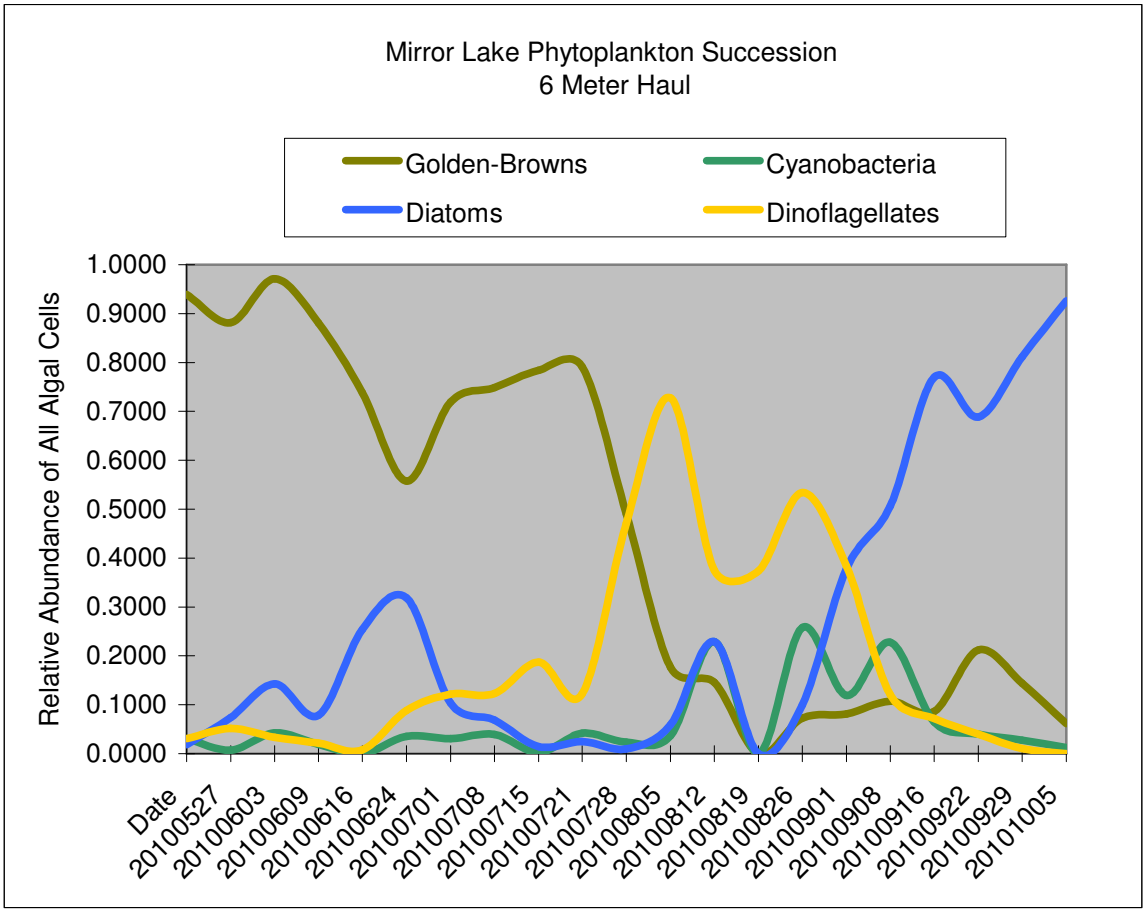

Figure 3-35: Mirror Lake Phytoplankton Succession, 6 Meter Haul

Asterionella, Rhizosolenia and *Tabellaria* were the most dominant Diatoms during 2010, with *Asterionella's* relative abundance peaking both in early July and early October (Figure 3-36). *Synura*, *Dinobryon* and *Chrysosphaerella* were the most dominant Golden-Browns with relative abundances greater than 30 percent from May through late-July (Figure 3-37). *Oscillatoria* and *Coeleosphaerium* were the most dominant cyanobacteria (Figure 3-38). *Oscillatoria* maintained a relative abundance greater than 30 percent from late July through mid-September. *Ceratium* was the only Dinoflagellate with relative abundances greater than 20 percent (Figure 3-39).

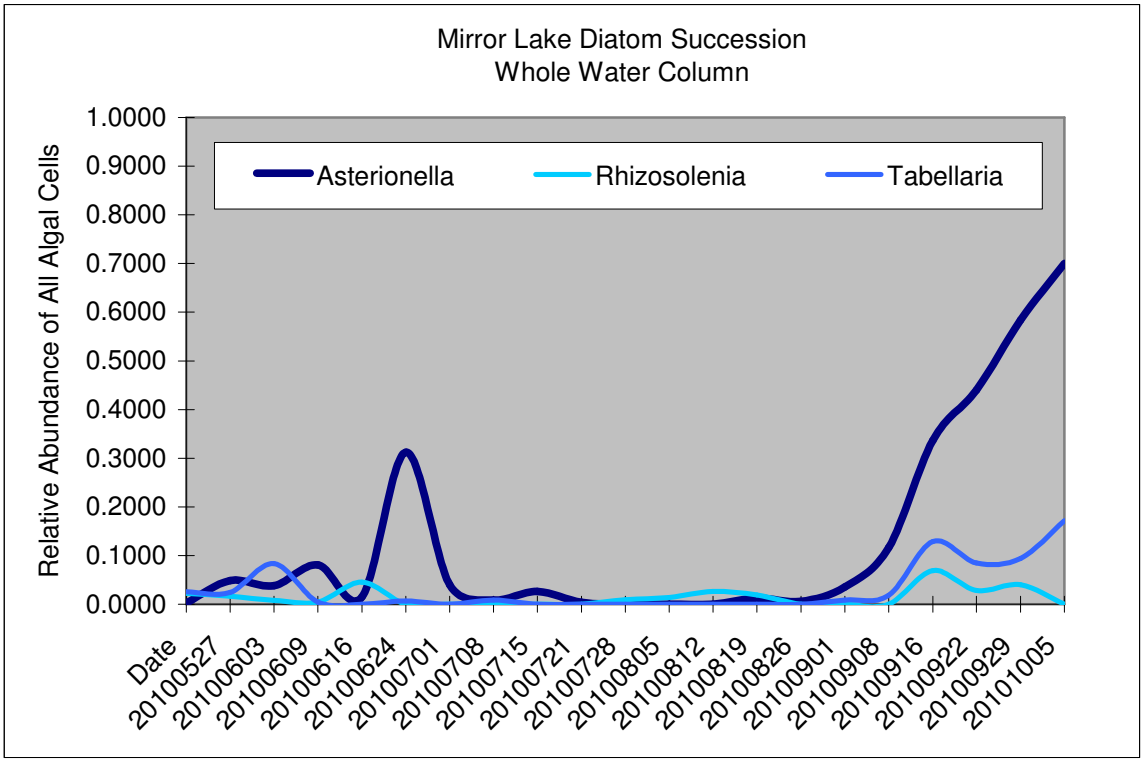

Figure 3-36: Mirror Lake Diatom Succession, Whole Water Column

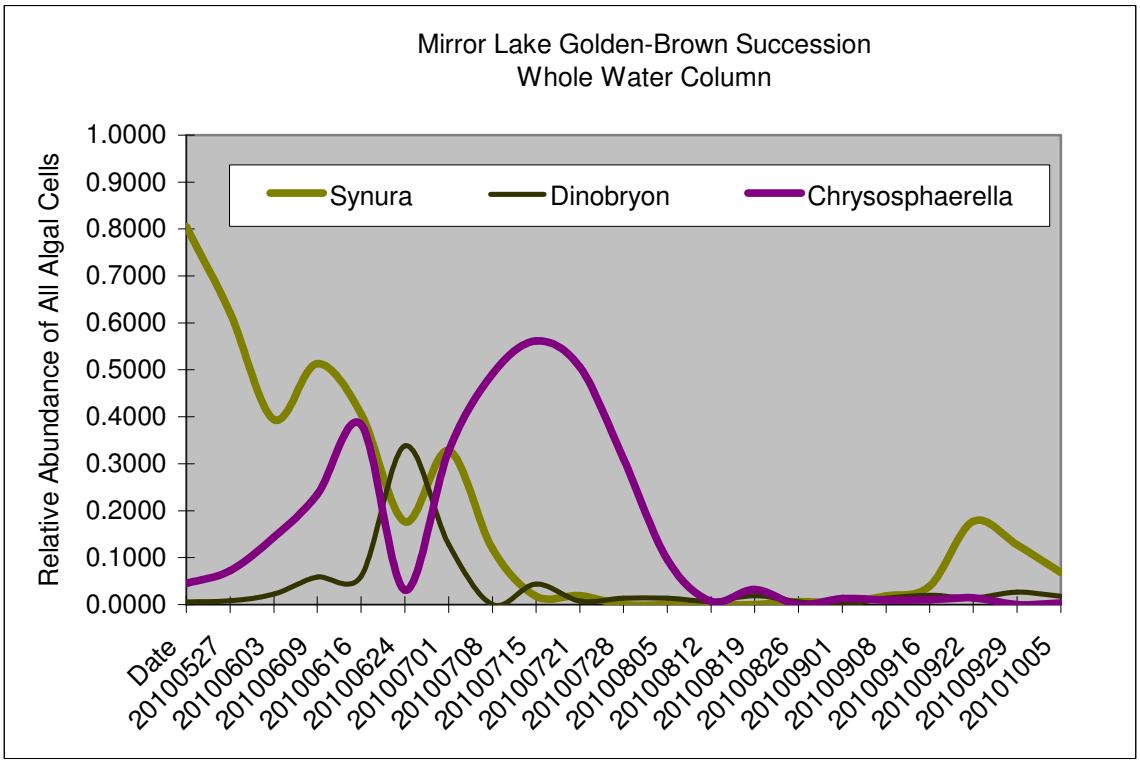

Figure 3-37: Mirror Lake Golden-Brown Succession, Whole Water Column

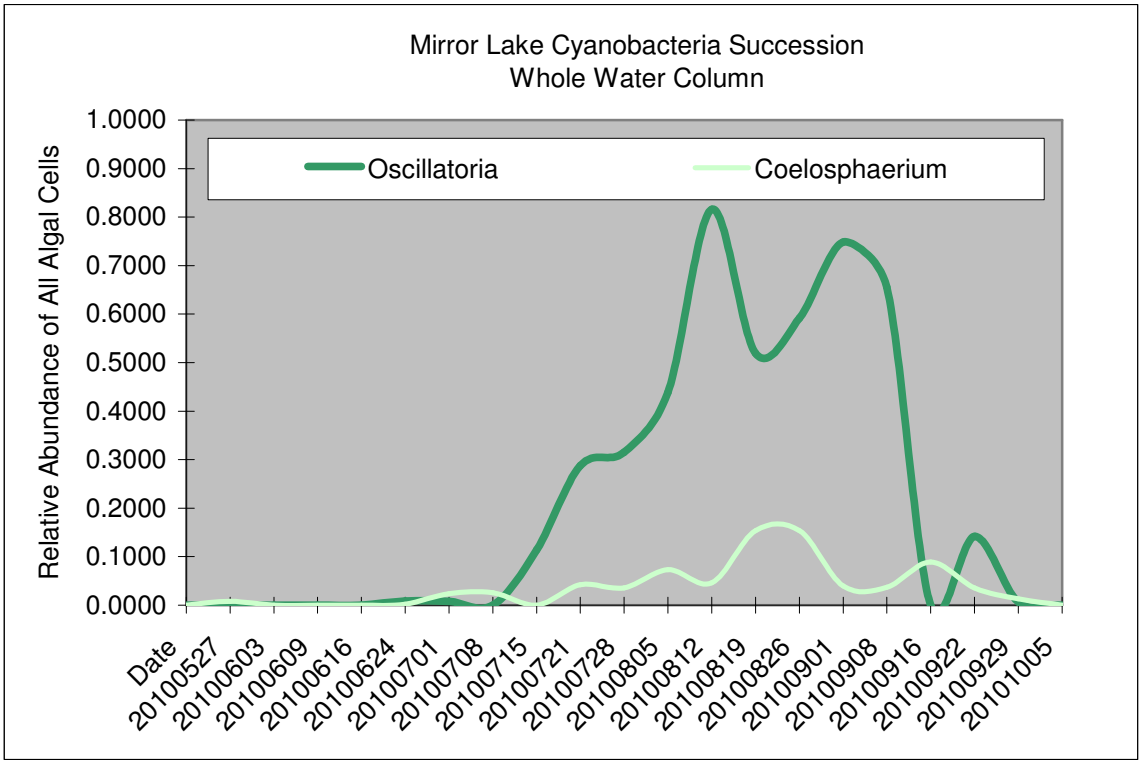

Figure 3-38: Mirror Lake Cyanobacteria Succession, Whole Water Column

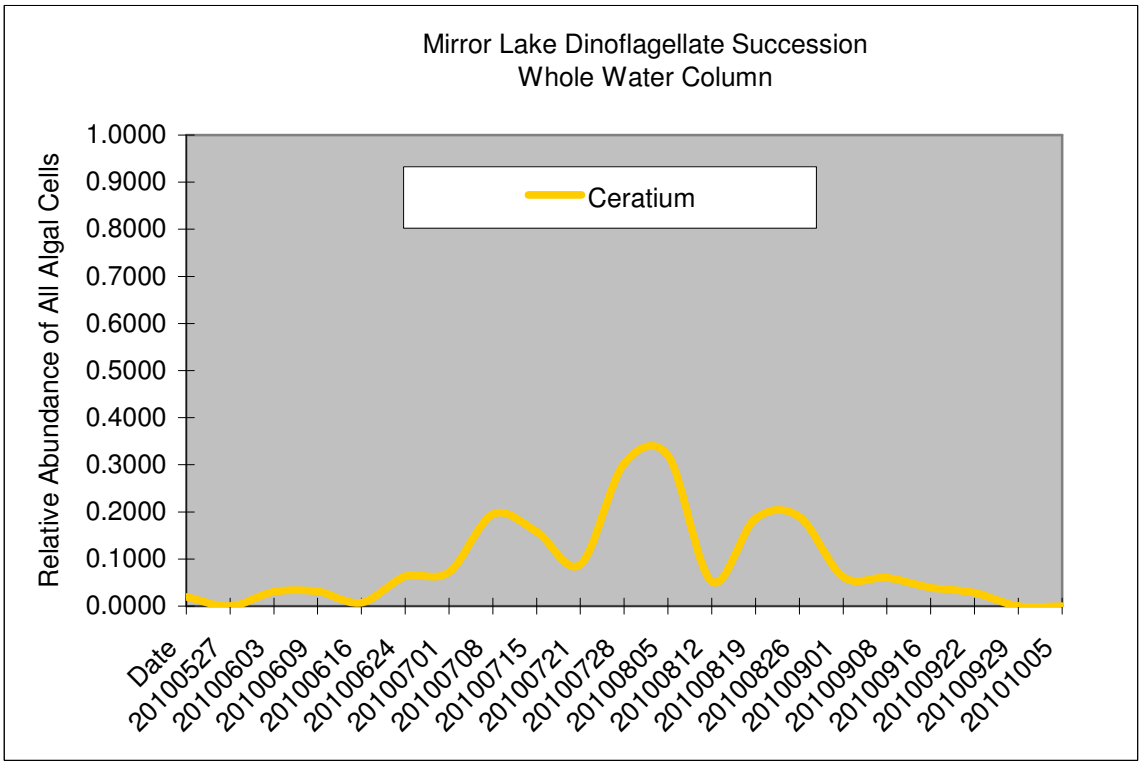

Figure 3-39: Mirror Lake Dinoflagellate Succession, Whole Water Column

Phytoplankton dominance was evaluated at the deep spot on August 26 for each one meter interval. Cyanobacteria was most abundant from 0-3 meters (*Coelospharium*), a mix of algal groups dominated from 3-6 meters (*Ceratium*, *Tabellaria*, and *Synura*), and cyanobacteria dominated from 6-12 meters (*Coelospharium*, *Oscillatoria*, *Anabaena*) (Table 3-5). *Oscillatoria* was the densest (29.61 %) phytoplanktonic species on August 26 (Table 3-6).

Table 3-5: Incremental Phytoplankton Relative Abundance and Density, August 26

Depth	Dominant Genus	Relative Abundance (%)		Density (cells/ml)
0-1 meter	*Coelospharium*	32.1		7.28
1-2 meter	*Coelospharium*	32.5		3.15
2-3 meter	*Coelospharium*	33.8		3.49
3-4 meter	*Ceratium, Tabellaria*	24.8	24.8	2.23
4-5 meter	*Synura*	39.8		0.80
5-6 meter	*Ceratium*	33.6		1.40
6-7 meter	*Coelospharium*	28.9		1.41
7-8 meter	*Oscillatoria*	94.7		51.89
8-9 meter	*Anabaena*	86.4		15.00
9-10 meter	*Oscillatoria*	54.8		2.80
10-11 meter	*Oscillatoria*	94.8		2.24
11-12 meter	*Oscillatoria*	64.4		2.18

Table 3-6: Whole Water Column Phytoplankton Density, August 26

Algal Family	Algal Genus	Whole Water Column Phytoplankton Relative Abundance (%)
Green	*Arthrodesmus*	0.13%
Green	*Closterium*	0.20%
Green	*Xanthidium*	0.07%
Green	*Scenedesmus*	0.07%
Green	*Sphaerocystis*	0.27%
Green	*Staurastrum*	0.67%
Cyanobacteria	*Coelospharium*	17.30%
Cyanobacteria	*Microcystis*	2.26%
Cyanobacteria	*Anabaena*	7.12%
Cyanobacteria	*Oscillatoria*	29.61%
Golden-Brown	*Chrysosphaerella*	6.25%
Golden-Brown	*Dinobryon*	0.60%
Golden-Brown	*Mallomonas*	0.73%
Golden-Brown	*Synura*	3.06%
Golden-Brown	*Uroglenopsis*	0.13%
Dinoflagellate	*Ceratium*	13.97%
Dinoflagellate	*Gymnodinium*	0.07%
Dinoflagellate	*Peridinium*	0.07%
Diatom	*Cyclotella*	0.00%
Diatom	*Melosira*	2.33%
Diatom	*Rhizosolenia*	2.46%
Diatom	*Asterionella*	0.27%
Diatom	*Fragillaria*	1.26%
Diatom	*Surirella*	0.07%
Diatom	*Synedra*	0.13%
Diatom	*Tabellaria*	10.91%

4.0 STUDY FINDINGS

Spring, non-stratified in-lake phosphorus concentration

Sample results from April 8, 2010 revealed that 10.8 ug/l P could be considered the spring, non-stratified in-lake phosphorus concentration for Mirror Lake (Table 4-1).

Table 4-1: Mirror Lake P Concentration, April

4/8/2010			
Depth (m)	TP (ug/l)	Volume (l)	Mass (kg)
1.00	12.0	2341204229	28.1
3.00	10.0	2036438871	20.4
7.00	9.7	887796578	8.6
10.00	9.8	325280846	3.2
Total		**5590720523**	**60.3**
Average	60.3 kg P / 5590720523 liters = **10.8 ug/l P**		

Early fall, maximum in-lake phosphorus concentration

Sample results from September 16 revealed that 13 to 14.7 ug/l reflects the summer maximum in-lake phosphorus concentration range for Mirror Lake (Tables 4-2 and 4-3) in 2010.

Table 4-2: Mirror Lake P Concentration, September with Vertical Mixing

9/16/2010					
Depth (m)	TP (ug/l) (Vol A)	TP (ug/l) (Vol B/C)	Volume A (l)	Volume B/C (l)	Mass (kg)
0.5	9.6	11.0	1135549548	120615545	12.2
2.0	9.6	11.0	1389422858	180923317	15.3
3.0	9.6	16.0	657009920	120615545	8.2
4.0	9.6	24.0	592583049	180923317	10.0
6.0	9.6	12.0	381521042	241231090	6.6
8.0	9.6	10.0	88463904	241231090	3.3
10.0	N/A	32.0	N/A	148422219	4.7
11.0	N/A	92.0	N/A	66339157	6.1
12.0	N/A	140.0	N/A	45868920	6.4
Total				**5590720523**	**72.9**
Average	72.9 kg P / 5590720523 liters = **13.0 ug/l P**				

Table 4-3: Mirror Lake P Concentration, September with Vertical and Horizontal Mixing

9/16/2010					
Depth (m)	TP (ug/l) (Vol A)	TP (ug/l) (Vol B/C)	Volume A (l)	Volume B/C (l)	Mass (kg)
0.5	9.6	11.0	1135549548	120615545	12.2
2.0	9.6	11.0	1389422858	180923317	15.3
3.0	9.6	16.0	657009920	120615545	8.2
4.0	N/A	24.0	N/A	773506366	18.6
6.0	N/A	12.0	N/A	622752132	7.5
8.0	N/A	10.0	N/A	329694994	3.3
10.0	N/A	32.0	N/A	148422219	4.7
11.0	N/A	92.0	N/A	66339157	6.1
12.0	N/A	140.0	N/A	45868920	6.4
Total			**5590720523**		**82.4**
Average	82.4 kg P / 5590720523 liters = **14.7 ug/l P**				

Fall, non-stratified in-lake phosphorus concentration

Sample results from October, 13 showed that 13.6 ug/l P reflects the fall, non-stratified in-lake phosphorus concentration for Mirror Lake (Table 4-4) in 2010.

Table 4-4: Mirror Lake P Concentration, October

10/13/2010			
Depth	TP (ug/l)	Volume (l)	Mass (kg)
1.000	14.0	2341204229	32.8
3.000	14.0	2036438871	28.5
7.000	12.0	887796578	10.7
10.000	12.0	279411926	3.4
11.000	12.0	45868920	0.6
Total		**5590720523**	**75.8**
Average	75.8 kg P / 6184999523 liters = **13.6 ug/l P**		

Internal phosphorus loading estimates for the summer season

An estimate of the internal P load was calculated using two methodologies (section 3.2), weekly in-situ summer P increase comparison and spring and summer in-situ P comparison.

The internal P load estimates ranged from 6.2 kg to 24.69 kg P. The most accurate estimate of the lake's internal P load was 24.69 kg, as this was based upon weekly sampling data.

The relationship between internal phosphorus loading and dominance of cyanobacteria

Internal P loading began in early July. By early August, cyanobacteria, including *Oscillatoria*, *Coelosphaerium* and *Anabaena*, were the dominant planktonic organisms in the water column after anoxia was well established. Once anoxia set in, internal phosphorus loads became available to cyanobacteria which have the ability to regulate buoyancy. This ability to regulate buoyancy gives the cyanobacteria a large advantage in seeking light and nutrient regimes for optimal growth (Sandgren 1988). During August, depths greater than 6 meters provided this optimum growth regime. By late August cyanobacteria continued to have the greatest relative abundance in the whole water column, including a presence in the upper 6 meters which continued through the first week of September (Figure 3-35). After September 8, most of the cyanobacteria retreated below 6 meters, with a tremendous decrease in the relative abundance of *Oscillatoria* after mid-September. This occurred approximately two weeks after the highest levels of cumulative internal P loading in early September (Figures 3-12 and Table 4-1).

Predicted internal loading impact and in-lake phosphorus concentration loading models

Several in-lake P load models were evaluated to determine which model best predicted in-lake P concentration. The initial model screening assumed that there was a watershed P load of 120.4 kg (Robert Hartzel, personal communication, 2010) and no internal P loading. Based on four deep spot samples collected on April 8 (1.0, 3.0, 7.0 and 10.0 meters) the volume-weighted, spring, in-lake P concentration is approximately 10.8 ug/l. Several models (Vollenweider 1976; Chapra 1975; Larsen and Mercier 1976; and Jones and Bachmann 1976) over-predicted and several models (Dillon and Rigler 1974; Reckhow 1977; Nürnberg 1998) under-predicted the in-lake P concentration. The Nürnberg model (1998, Eq. 2) predicted an in-lake P concentration of 8.6 ug/l, the closest predicted value (Table 4-5) to the April 8 volume-weighted in-lake P concentration (Table 4-2). The downside of predictive P loading models is that they do not incorporate internal P loading.

The Nürnberg model was modified, accounting for internal P loading, to predict spring, in-lake P concentrations (Nürnberg 1998, Eq. 4) or fall, in-lake P concentrations (Nürnberg 1998, Eq. 5) (Table 4-6). When an internal P load of 24.69 kg (section 3.2) is applied, Equation 4 and Equation 5 predict an in-lake concentration of 10.4 ug/l (12 months of internal P load settling) and 14.9 ug/l (0 months of internal P load settling), respectively. Assuming that internal P loads settle for approximately 10 months, (July or the onset of internal loading through April) Equation 4 can be further modified, yielding

an in-lake P concentration of 11.1 ug/l. This is a 0.3 ug/l difference from the volume-weighted, in-lake P concentration value derived from the April 8 data (Table 4-1). If the internal P loads were assumed to settle for 3 months (July-Sept), Equation 4 could be modified, yielding an in-lake P concentration of 13.8 ug/l. This relates well with the volume-weighted, in-lake P concentration values derived from the October 13 data (13.6 ug/l) but underestimated the September 16 data (14.7 ug/l) (Tables 4-2 through 4-4). However, the Nürnberg model output (Nürnberg 1998, Eq. 5) predicts a value of 14.9 ug/l if no settling of internal P loads occurs. Additional P data for a more detailed profile and within other parts of the lake to verify the extent of lateral P transport or increased fluid dynamics modeling may have yielded a more accurate volume-weighted in-lake P estimate

Table 4-5: In-lake P Concentration Model Predictions with No Internal P Loading

Parameter	Symbol	Units	Equation	Value (Study Period)
Watershed area	Aw	m^2	measured	5,905,405
Lake area	Al	m^2	measured	1,346,595
Lake volume	V	m^3	measured	5,590,720
Lake discharge	Q	m^3	Q=Wi-(1-lake evap)	3,998,132
Hydraulic residence time	T	yr	T=V/Q	1.40
Flushing rate	F	yr^{-1}	Flushing Rate = 1/T	0.72
Mean depth	Z	m	measured	4.1
Watershed annual loading, phosphorus, WS	Wext	kg	modeled	**120.4**
Internal P load, in-situ fall increase, partial net estimate, Nurnberg and LaZerte, 2001	Wint, partial net	kg	modeled	**0.0**
Total annual loading, phosphorus	L	kg	calculated sum	**120.4**
Areal water load or surface overflow rate	qs	m/yr	Z(F) or Z/T	2.94
Annual precip., USDA, NOAA, 1971-2001	Wp	m/yr	chart	1.1026
Annual evapotranspiration percent, Randall 1996	We	m/yr	chart	0.4750
Annual runoff percent, Randall	Wr	m/yr	chart	0.5250
Pan Evaporation	pan evap	m/yr	Table	32.0000
Water inflow	Wi	m^3	Wi=qs*A	4,585,112
P Retention coefficient, Nurnberg, no P Lint	Rpred	N/A	Rpred=15/(18+qs)	0.7164
Total external areal P loading	Lp or Lext	$g/m^2/yr$	Lext=P*1000/Al	0.0894
Total internal areal P loading	Lint	$g/m^2/yr$	Lint=P*1000/Al	0.0000
Vollenweider 1976, in-lake P concentration, spring	V (1976)	mg/L or g/m^3	$P = \frac{Lp}{qs}\left[\frac{1}{1+\sqrt{\frac{z}{qs}}}\right]$	0.0139
Chapra 1975, in-lake P concentration, spring	C (1975)	mg/L or g/m^3	P=Lp(1-r)/(Z*F)	0.0147
Dillon and Rigler 1974, in-lake P concentration, spring	D-R (1974)		P=Lp*(1-Rp)/qs	0.0076
Kirchner and Dillon 1975, in-lake P concentration, spring	K-D (1975)		P=Lp*(1-Rp)/qs	0.0076
Larsen and Mercier 1976, in-lake P concentration, spring	L-M (1976)		P=Lp(1-Rlm)/qs	0.0139
Jones and Bachman 1976, in-lake P concentration, spring	J-B (1976)		P=0.84(Lp)/(Z(0.65+F))	0.0134
Reckhow 1977, in-lake P concentration, spring	Rg (1977)		P=Lp/(11.6+1.2(Z(F)))	0.0059
Nürnberg 1998, in-lake P concetration, spring, No internal P load	N(1998, Eq. 2)	mg/L or g/m3	P=((Lext/qs(1-Rpred))	0.0086

Table 4-6: Nürnberg, In-lake P Concentration Predictions

Parameter	Symbol	Units	Equation	Value (Study Period)
Watershed area	Aw	m^2	measured	5,905,405
Lake area	Al	m^2	measured	1,346,595
Lake volume	V	m^3	measured	5,590,720
Lake discharge	Q	m^3	Q=Wi-Lpevap	3,998,132
Hydraulic residence time	T	yr	T=V/Q	1.40
Flushing rate	F	yr^{-1}	Flushing Rate = 1/T	0.72
Mean depth	Z	m	measured	4.1
Watershed annual loading, phosphorus, WS	Wext	kg	modeled	**120.4**
Internal P load, in-situ fall increase, partial net estimate, Nurnberg and LaZerte, 2001	Wint, partial net	kg	modeled	**24.69**
Total annual loading, phosphorus	L	kg	calculated sum	**145.1**
Areal water load or surface overflow rate	qs	m/yr	Z(F) or Z/T	2.94
Annual precip., USDA, NOAA, 1971-2001	Wp	m/yr	chart	1.1026
Annual evapotranspiration percent, Randall	We	m/yr	chart	0.4750
Annual runoff percent, Randall	Wr	m/yr	chart	0.5250
Pan Evaporation	pan evap	m/yr	Table	32.0000
Lake Evaporation	lake evap	m^3	Wi=qs*A	4,585,112
P Retention coefficient, Kirchner and Dillon 1975	Rp	N/A	Rpred=15/(18+qs)	0.7164
Total external areal P loading	Lp or Lext	$g/m^2/yr$	Lext=P*1000/Al	0.0894
Total internal areal P loading	Lp	$g/m^2/yr$	Lint=P*1000/Al	0.0183
Nürnberg 1998, in-lake P concetration, fall Internal P load settling for 12 months	N (1998), Eq. 4	mg/L or g/m^3	P=(Lext+Lint)/qs(1-Rpred)	0.0104
Nürnberg 1998, in-lake P concentration, spring Internal P load settling for 10 months	N(Eq. 4 modified internal load settling time)		P=(Lext/qs(1-Rpred) + Lint/qs*(1-(10/12)*Rpred))	0.0111
Nürnberg 1998, in-lake P concetration, fall Internal P load settling for 3 months	N(Eq. 4 modified internal load settling time)		P=(Lext/qs(1-Rpred) + Lint/qs*(1-(3/12)*Rpred))	0.0137
Nürnberg 1998, in-lake P concentration, fall Internal P load settling for 2 months	N(Eq. 4 modified internal load settling time)		P=(Lext/qs(1-Rpred) + Lint/qs*(1-(2/12)*Rpred))	0.0141
Nürnberg 1998, in-lake P concentration, fall Internal P load settling for 1 month	N(Eq. 4 modified internal load settling time)		P=(Lext/qs(1-Rpred) + Lint/qs*(1-(1/12)*Rpred))	0.0145
Nürnberg 1998, in-lake P concetration, fall, Internal P load settling for 0 months	N (1998), Eq. 5		P=(Lext/qs(1-Rpred) + Lint/qs)	0.0149

5.0 CONCLUSIONS AND RECOMMENDATIONS

Mirror Lake in Tuftonboro, New Hampshire, was designated in the 2008 Federal Section 303(d) list as a waterbody impaired for primary contact recreation; a result of recurring cyanobacteria surface scums.

The watershed plan currently being developed by Geosyntec Consultants will account for internal P loading estimates according to this report and prioritize watershed and in-lake treatment measures using this information.

Minimizing excessive cyanobacteria cell production and resultant cyanobacteria scums will likely require summer and fall, fully-mixed in-lake P concentrations to not exceed 12 ug/l and maybe less. The Nürnberg (1998, Eq. 4) model estimates the annual permissible load to achieve an in-lake goal of 12 ug/l P is approximately 105.09 kg P, which includes internal P loading (24.69 kg) but does not factor-in any internal P load settling. Watershed modeling estimates by Geosyntec Consultants indicate watershed P loads of 120.4 kg P. Watershed P loads and internal P loads combined account for an estimated 145.1 kg. Assuming the internal P load remained and did not settle during the period of internal loading, a load reduction of 40.0 kg P resulting in an 80.4 kg annual P load from the watershed would be needed to achieve a fall, in-lake, 12 ug/l P concentration goal. Phytoplankton response is related to P load reductions or P increases from both the watershed and in-lake sources. All P load reductions will result in water quality improvements, including increased clarity and reduced incidences and magnitudes of cyanobacteria blooms and scums. Phosphorus reductions typically coincide with improvements in lake water quality.

If the Mirror Lake watershed was modeled to show a completely forested condition or "best-case" scenario, the watershed P load would be approximately 75 kg, yielding a spring, in-lake condition of 5.4 ug/l P, assuming no internal P loading. There is the potential to remove more than 40 kg P annually and achieve the "best-case" scenario if lake restorative techniques could eliminate internal P loading. To achieve a summer epilimnetic P concentration of 8.0 ug/l, the nutrient criteria for oligotrophic lake's aquatic life use designation, 9 kg P would need to be removed, assuming no internal P load occurrence. To achieve a summer epilimnetic concentration of 8.0 ug/l, 44 kg P would need to be removed, assuming a 24.69 kg internal P load reoccurs annually and settles no less than 10 months.

5.1 Watershed Management

Everyone lives in a watershed. What you do in your watershed can affect the entire watershed and can impact the health of the waterbodies that we recreate on and depend upon. The health of our waterbodies largely depends on the quality of our stormwater. Stormwater is water from rain or melting snow that does not soak into the ground. In a forest, meadow, or other natural landscape, stormwater soaks into the ground and naturally filters through the soil. When forests and meadows are developed, they are replaced with neighborhoods, shopping centers, and other areas that introduce impervious surfaces such as rooftops, roads, parking lots, and even lawns. Impervious surfaces prevent rain or melting snow from soaking into the ground and create excess stormwater runoff and stormwater pollution (McCarthy 2011).

It is essential that best management practices or low impact design techniques be utilized by everyone. These best management practices include: minimizing areas of driveways and paths, maintaining as much natural buffer as possible with minimization of maintained lawns, creating "rain gardens" or other infiltration techniques for roof runoff, and directing driveway drainage either away from the lake or to areas where infiltration is possible. Increasing lake and tributary setbacks for septic systems and implementing stormwater BMPs or low impact design retrofits for developed land in the watershed will be a significant benefit in the long-term maintenance of watershed health and lake quality. Equally important is the maintenance of forest cover throughout the watershed. Section 3.0 describes that by late-July, internal P loads of only 13 kg resulted in an increase in cyanobacteria below 6 meters; by mid-August, internal loads of approximately 20 kg P resulted in increased cyanobacteria in the upper water column. Even small P load reductions, totaling less than 20 kg P, will likely result in significant water quality improvements if no increased P loading occurs from other watershed sources to the lake.

5.2 In-lake Restoration: Hypolimnetic Phosphorus Inactivation

In-lake restorative techniques have been researched for many years. Case studies evaluate the restorative and management techniques for lakes (Cooke et al. 2005). Even though all lakes and watersheds are physically, chemically and biologically different, one or a combination of watershed management and lake restorative techniques may provide short or long-time remedial actions that improve lake quality. There are several in-lake restorative actions that have proven to reduce internal sediment P loading to some lakes. Although there are no inexpensive means to achieve sediment P reductions, there are techniques that are more cost-effective than others. Both limnologists and engineers have evaluated a series of lake restorative techniques (Cooke et al. 1977; 1986; 2005). Each hypolimnetic phosphorus inactivation technique was evaluated by comparing case studies throughout the world. These restorative techniques were examined and rated by the pros and cons, history of lake quality improvements and the methodology's cost effectiveness. These in-lake techniques include aeration, circulation, biomanipulation, dredging, water exchange and a series of chemical inactivation processes. One proven technique considered for use in cases of sediment phosphorus loading is phosphorus inactivation with aluminum salts. New Hampshire was the first state to use an innovative delivery system that injected a mixture of aluminum salts into the lake hypolimnion. A discussion of aluminum salts injection and New Hampshire's research on hypolimnetic injection are presented below.

Phosphorus precipitation and sediment P inactivation through aluminum salts injection are lake restoration techniques that reduce phosphorus in the water column or at a specific thermal stratification level through P stripping and in the sediment through chemical bonding. Sediment phosphorus inactivation results in longer-term lake quality improvement when compared to water column precipitation. Sediment inactivation is particularly useful in accelerating lake improvement in those lakes that have a significant internal phosphorus load. (Cooke et al. 1977; 2005; Larsen et al. 1979). It is important to stress that all watershed P sources should be reduced or eliminated prior to the use of this technique. Increased watershed P inputs would counteract any in-lake restorative techniques, minimize lake quality improvements and would increase the cost/benefit

ratios of any in-lake project. The key to success for an in-lake phosphorus reduction project is the simultaneous reduction of watershed phosphorus loading to the lake.

Aluminum salts injection benefits include in-lake phosphorus reduction, decrease or elimination of internal sediment P loading, increased transparency, decreased chlorophyll, reductions in algal and cyanobacteria abundance and cell dominance shifts from cyanobacteria to other more beneficial algal populations.

Potential P inactivation drawbacks correspond to chemical reactions in the water from added compounds. Lakes with low buffering capacity (low ANC) are particularly vulnerable to complications following additions of aluminum sulfate. Small doses of aluminum sulfate can exhaust the buffering capacity to a point that causes lake pH to fall below 6.0. Once this occurs, aluminum may be released from the aluminum phosphate compound which could potentially cause aluminum toxicity in the lake. Knowing the lake chemistry before aluminum salts are used as inactivates is extremely important to the project's success. Research methods to ameliorate aluminum toxicity involve adding salts like sodium aluminate to buffer acidity. Increased aquatic plant growth due to increased light transmission may be considered a drawback by some lake users. As lake clarity increases, sunlight penetration extends to greater depths. This allows increased aquatic plant production throughout the littoral zone. A hypolimnetic treatment is desired over whole lake treatments because the dense aluminum floc in the upper waters can disrupt and reduce important invertebrate populations.

Hypolimnetic aluminum salts treatment research efforts were initiated at Kezar Lake, located in North Sutton, New Hampshire. Lyon Brook, the main tributary to Kezar Lake, received an extraordinary phosphorus load from the discharge of treated sewage effluent from the now defunct New London Sewage Treatment Facility (Connor and Smith 1983). The project plan was first to eliminate or reduce the watershed input of P to the Kezar Lake watershed; this included the piping of sewage to the Sunapee Wastewater Facility, watershed protection ordinances, low impact development techniques and wetlands manipulation. Once these watershed protection techniques were established in the New London, Lyon Brook watershed, in-lake restorative techniques that included aluminum sulfate and sodium aluminate were used as sediment phosphorus inactivants to improve lake quality (Connor and Smith 1986). The treatment occurred during June of 1984. A ten-year monitoring program provided an extensive lake database to evaluate the short-and-long-term effectiveness of sediment phosphorus inactivation as a lake restoration technique (Connor and Martin 1989; Connor and Smagula 2000). Within a year of the treatment a reduction in the hypolimnetic oxygen depletion resulted in hypolimnetic oxygen maintenance, a decrease in algal and cyanobacteria abundance (measured by chlorophyll-a concentration and microscopic cell counts), an increase in lake clarity from 0.5 M to over 3.0 M, a shift from cyanobacteria dominance to algal species typical to New Hampshire lakes and ponds, and an increase in trophic status from eutrophic to mesotrophic. No negative impacts to lake organisms or lake chemistry were detected in the post-treatment monitoring program (Connor and Smagula 2000). Within five years the variability of lake trophic conditions stabilized. More than twenty-five years later, the lake is still showing signs of good water quality as seen through DES Volunteer Lake Assessment Program sampling results.

If aluminum salts treatment for Mirror Lake were necessary, it would likely cost more than $100,000 (30 acre in-lake treatment at $3500/acre). Some treatments are met with limited success, especially if watershed BMPs have not been implemented, resulting in temporary improvements as elevated phosphorus loading continues and settles in the lake, uncapped by the previous aluminum salt treatment and therefore potentially available for algal uptake. Occasionally, an increase in algal or cyanobacteria blooms may occur after treatment. In-lake treatments would only be considered following implementation of the Mirror Lake Watershed Management Plan BMPs as outlined in the plan and as needed to achieve watershed phosphorus source reductions to pre-development or low-level impact conditions. Possible scenarios where phosphorus inactivation treatments may not yield the desired water quality improvement should be considered. Most importantly, in-lake restoration using hypolimnetic phosphorus inactivation cannot be considered without a source of funding.

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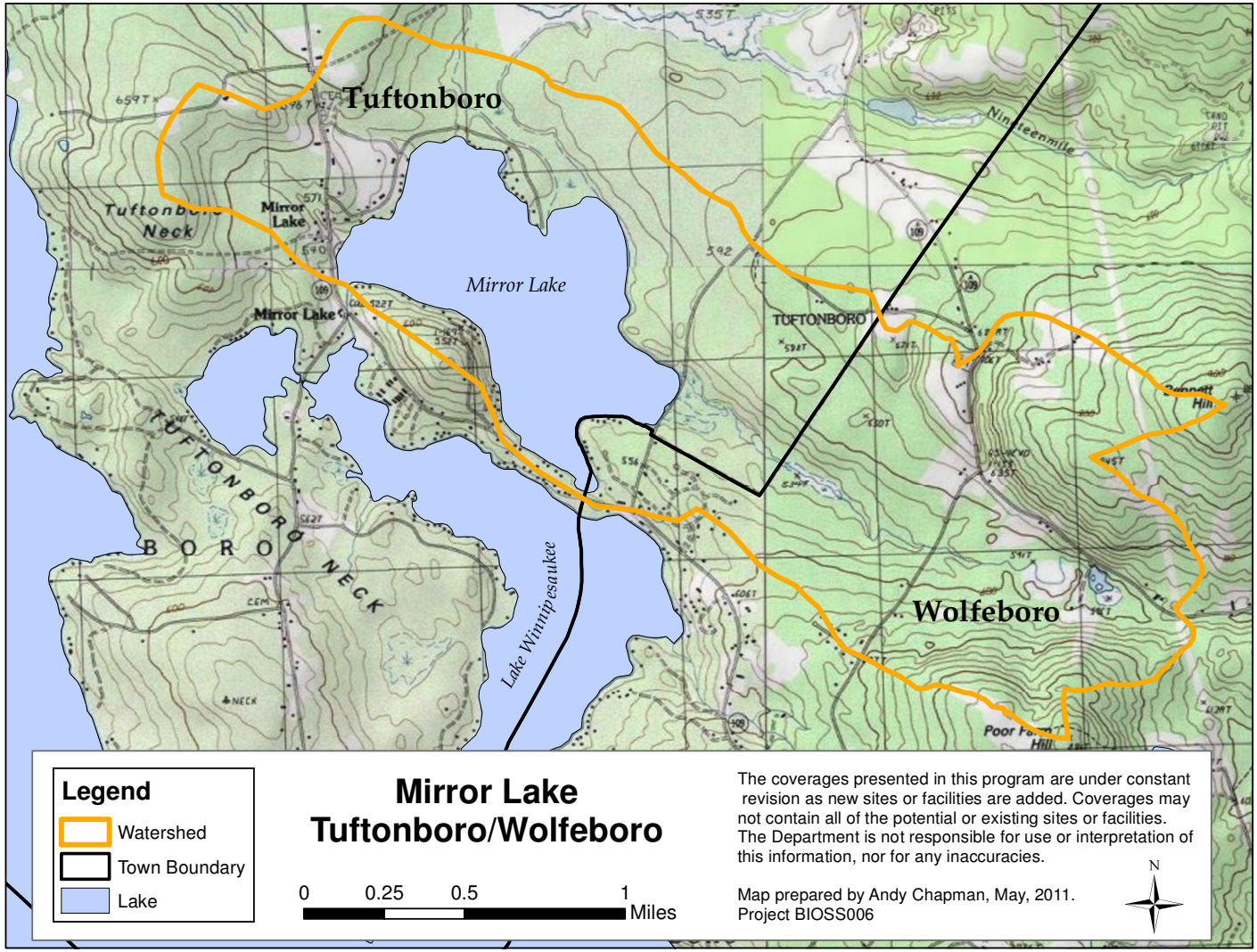
APPENDICES

Appendix A: Mirror Lake Watershed



Appendix B: New Hampshire Consolidated Listing Methodology Summary

New Hampshire is required to report on a two year cycle the water quality status of the state's surface waters in accordance with Section 305(b) and 303(d) of the Federal Water Pollution Control Act as last reauthorized by the Water Quality Act of 1987 [PL92-500, commonly called the Clean Water Act (CWA)], and New Hampshire Statutes Chapter 485-A:4.XIV (New Hampshire 2008 SECTION 305(b) and 303(d), Surface Water Quality Report and RSA 485-A:4.XIV Report to the Governor and General Court).

The "305(b) Report" describes the quality of the state's surface waters and an analysis of the extent to which all such waters provide for the protection and propagation of a balanced population of shellfish, fish and wildlife, and allow recreational activities in and on the water. Section 303(d) requires submittal of a list of waters (i.e., the 303(d) List) that are:

- impaired or threatened by a pollutant or pollutant(s),
- not expected to meet water quality standards within a reasonable time even after application of best available technology standards for point sources or best management practices for nonpoint sources and,
- require development and implementation of a comprehensive water quality study (i.e., called a Total Maximum Daily Load or TMDL study) that is designed to meet water quality standards.

Nutrient criteria developed by NHDES and the Nutrient Criteria Committee (Trowbridge 2009) are used to assess both the primary contact recreation (PCR) and the aquatic life uses (ALU) in New Hampshire lakes.

For PCR assessments, the nutrient response variables chlorophyll-a (Chl-a) and cyanobacteria scums are secondary indicators for PCR assessments. They can cause a "not support" assessment but, by themselves, cannot result in a "full support" designation (the primary indicator *E. coli* is needed for a "full support" assessment). The logic is that elevated Chl-a levels or the presence of cyanobacteria scums interfere with the aesthetic enjoyment of swimming and, in the case of cyanobacteria, pose a potential public health issue for recreational uses. If Chl-a or cyanobacteria cause a "not support" assessment, the causal variable total phosphorus (TP) is also assessed as not supporting PCR.

For aquatic life use assessments, the combination of the causal variable total phosphorus (TP) and the response variable Chl-a is one of three core indicators (pH and DO are the other two) that are required to make a "full support" assessment. Chl-a dictates the assessment if both Chl-a and TP data are available and the assessments differ. The results are combined according to the following decision matrix:

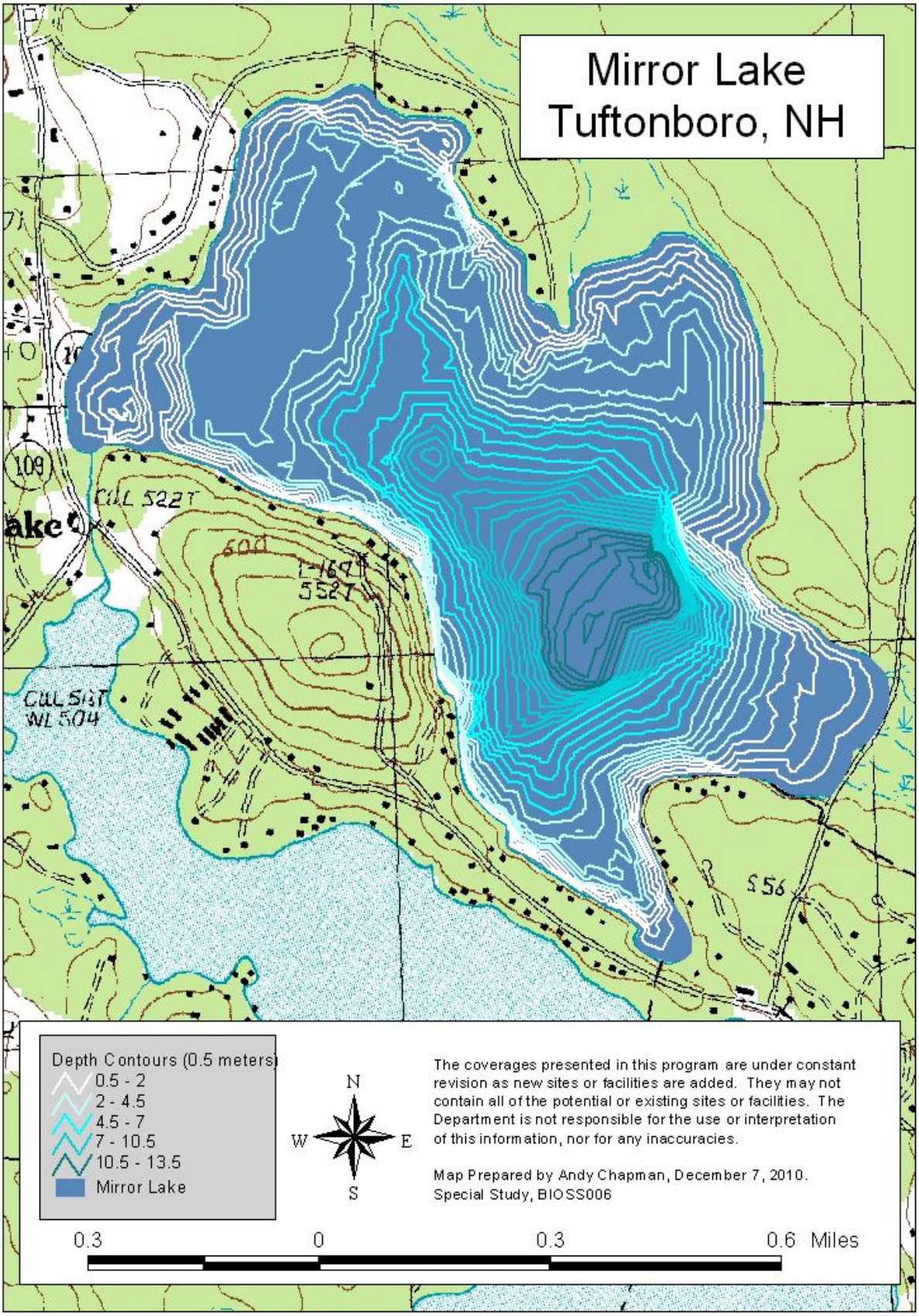
	TP threshold exceeded	TP threshold not exceeded	Insufficient information for TP
Chl-a threshold exceeded	Impaired	Impaired	Impaired
Chl-a threshold not exceeded	Fully supporting	Fully supporting	Fully supporting
Insufficient information for Chl-a	Impaired	Fully supporting	Insufficient information

The ALU nutrient criteria vary by lake trophic class. Trophic classes are determined by primary production or plant biomass with increasing biomass from oligotrophic to eutrophic lakes. The logic is that each trophic class has a given phytoplankton biomass (Chl-a) representing a balanced, integrated and adaptive community for that trophic class, and exceedences of the Chl-a criterion suggest the phytoplankton community is out of balance (i.e., not fully supported). The ALU nutrient criteria by trophic class are depicted in the table below:

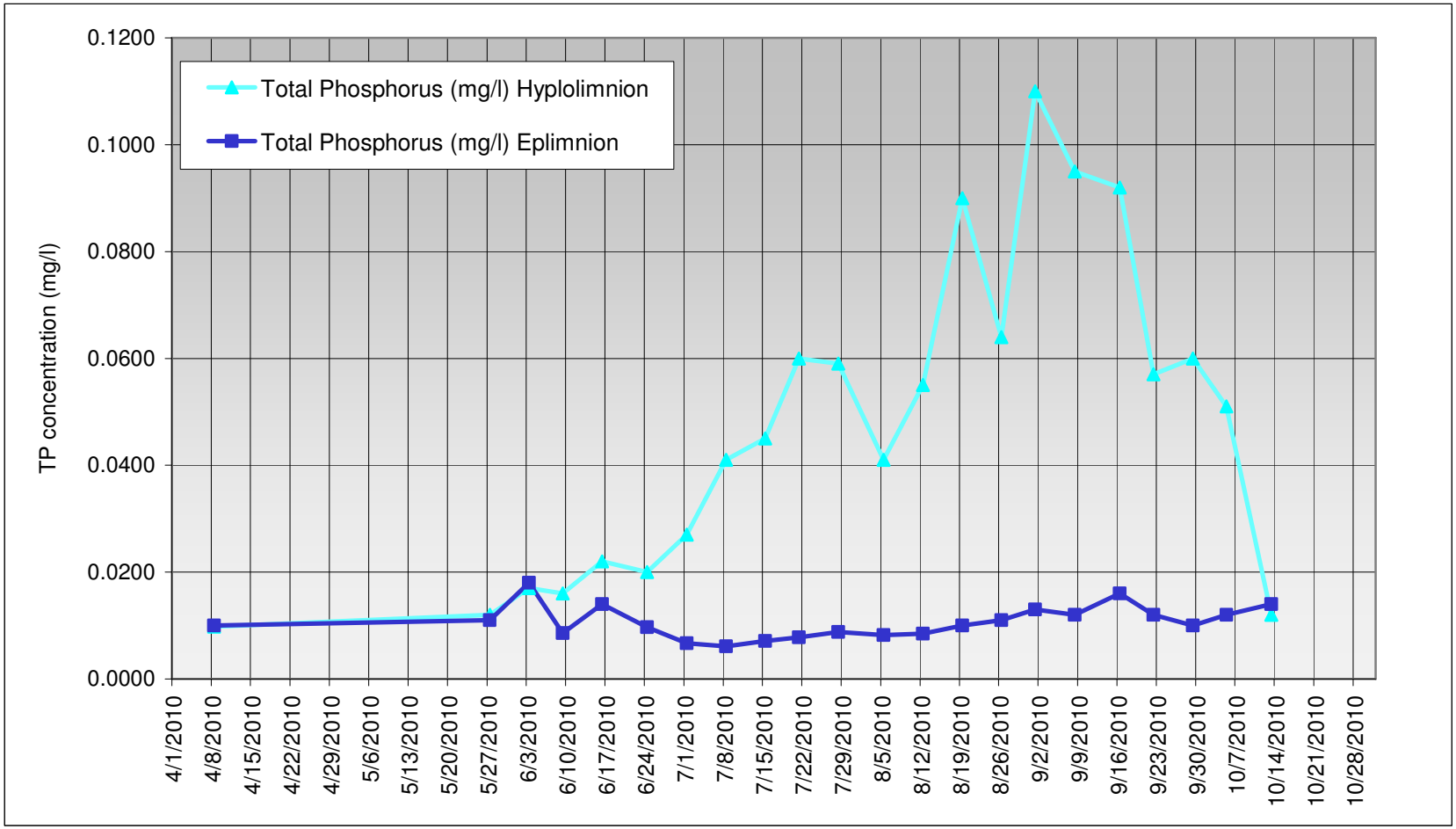
Aquatic Life Use Nutrient Criteria by Trophic Class

	TP (ug/L)	Chl (ug/L)
oligotrophic	< 8.0	< 3.3
mesotrophic	8.0 – 12.0	3.3 – 5.0
eutrophic	> 12 - 28	> 5 - 11

Appendix C: Mirror Lake Bathymetry



Appendix D: Epilimnetic and Hypolimnetic Phosphorus Concentrations April-October



Epilimnion sample depth = 3 meters, * 4 M sample collected May 27.
Hypolimnion sample depth = 11 meters, * 10 M sample collected April 8, 2010, and May 27.

Appendix E: Comparison of Phosphorus Mass and Concentration in the Upper (Epi/Meta) and Lower (Hypo) Layers of Mirror Lake

Date	Phosphorus (mg/l) 3 meters [over hypo, 9-14 meters]	Epi./Meta. Phosphorus [1] (kg) [over hypo 9-14 meters]	Phosphorus (mg/l) [not over hypo, 9-14 meters]	Epi./Meta. Phosphorus [1] (kg) [not over hypo 9-14 meters]	Phosphorus (mg/l) 11 meters	Hypo. Phosphorus [1] (kg)	Total Phosphorus Load (kg)	Volume weighted lake P concentration (mg/l)	Internal P load (kg) post 7/1/10 remaining in Hypo.	Internal P load (kg) post 8/19/10 transported to Meta./Epi.	Weekly Total Internal P load (kg) in lake
4/8/2010	0.0100	10.9	0.0100	42.4455	0.0098	2.6	55.86	0.0100			
5/27/2010	0.0110	11.9	0.0110	46.6901	0.0120	3.1	61.76	0.0110			
6/3/2010	0.0180	19.5	0.0180	76.4019	0.0170	4.4	100.37	0.0180			
6/9/2010	0.0086	9.3	0.0086	36.5031	0.0160	4.2	50.01	0.0089			
6/16/2010	0.0140	15.2	0.0140	59.4237	0.0220	5.7	80.36	0.0144			
6/24/2010	0.0097	10.5	0.0097	41.1721	0.0200	5.2	56.91	0.0102			
7/1/2010	0.0067	7.3	0.0067	28.4385	0.0270	7.0	42.75	0.0076	1.8		1.8
7/8/2010	0.0061	6.6	0.0061	25.8918	0.0410	10.7	43.20	0.0077	5.5		5.5
7/15/2010	0.0071	7.7	0.0071	30.1363	0.0450	11.7	49.57	0.0089	6.5	1.1	7.6
7/21/2010	0.0078	8.5	0.0078	33.1075	0.0600	15.6	57.21	0.0102	10.4	1.8	12.3
7/28/2010	0.0088	9.6	0.0088	37.3520	0.0590	15.4	62.28	0.0111	10.2	2.9	13.1
8/5/2010	0.0082	8.9	0.0082	34.8053	0.0410	10.7	54.39	0.0097	5.5	2.3	7.8
8/12/2010	0.0085	9.2	0.0085	36.0787	0.0550	14.3	59.64	0.0107	9.1	2.6	11.7
8/19/2010	0.0100	10.9	0.0096	40.6497	0.0900	23.5	74.96	0.0134	18.2	4.2	22.5
8/26/2010	0.0110	11.9	0.0096	40.6497	0.0640	16.7	69.27	0.0124	11.5	5.3	16.8
9/1/2010	0.0130	14.1	0.0096	40.6497	0.1100	28.7	83.43	0.0149	23.5	7.5	30.9
9/8/2010	0.0120	13.0	0.0096	40.6497	0.0950	24.8	78.44	0.0140	19.5	6.4	26.0
9/16/2010	0.0160	17.4	0.0096	40.6497	0.0920	24.0	82.00	0.0147	18.8	10.7	29.5
9/22/2010	0.0120	13.0	0.0096	40.6497	0.0570	14.9	68.53	0.0123	9.6	6.4	16.0
9/29/2010	0.0100	10.9	0.0096	40.6497	0.0600	15.6	67.14	0.0120	10.4	4.2	14.7
10/5/2010	0.0120	13.0	0.0096	40.6497	0.0510	13.3	66.97	0.0120	8.1	6.4	14.5
10/13/2010	0.0140	15.2	0.0096	40.6497	0.0120	3.1	58.97	0.0105	destratified	destratified	0

[1] Calculated based upon 2010 bathymetry data. Epilimnion/Metalimnion volume directly over 9 meter depth plane = 1,085,539,904 liters. Epilimnion/Metalinion volume not directly over 9 meter depth = 4,244,550,322 liters. Hypolimnion depth = 260,630,296 liters.

[2] Epilimnion sample depth is 3 meters, except for May 27, 2010, 4 meter sample depth. Hypolimnion sample depth is 11 meters, except for April 8, 2010, and May 27, 2010, 10 meter sample depth.