Webster Lake
Franklin, New Hampshire

Phosphorus and Cyanobacteria Study

NEW HAMPSHIRE DEPARTMENT OF Environmental Services

2010

DES-R-WD-10-14

Webster Lake
Phosphorus and Cyanobacteria Study

Final Report, 2010
Amended 2011

New Hampshire Department of Environmental Services

Water Division, Watershed Management Bureau, Biology Section

29 Hazen Drive, Concord, NH 03301

(603) 271-2963

www.des.nh.gov

Andrew Chapman, Clean Lakes Program Coordinator
Jody Connor, Limnology Center Director
Principal Authors

Thomas S. Burack
Commissioner

Michael Walls
Assistant Commissioner

Harry T. Stewart
Division Director

Robert H. Estabrook
Chief Aquatic Biologist

Acknowledgements

The Biology Section Staff of the Department of Environmental Services is acknowledged for its professional assistance in the field and laboratory. Particular thanks to Biology Intern, Josh Connor and Biology Staff, Walter Henderson, Amy Smagula and Scott Ashley.

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

Title Page i
Acknowledgments ii
Table of Contents ii
List of Figures iii
List of Tables iii

1.0 INTRODUCTION AND PURPOSE 1
1.1 Introduction 1
1.3 Purpose 4
2.0 METHEDOLOGY 5
2.1 Webster Lake, in-lake 5
2.2 Sucker Brook 5
3.0 STUDY DATA 5
3.1 Temperature/ Dissolved Oxygen 5
3.2 Phosphorus 9
3.3 Chlorophyll-a 14
3.4 Secchi Depth 19
3.5 Plankton 19
3.6 Sucker Brook 21
4.0 STUDY PURPOSE FINDINGS 23
5.0 CONCLUSIONS AND RECOMMENDATIONS 27
5.1 Watershed Management 30
5.2 In-lake Treatment- Phosphorus Inactivation 30

Webster Lake Phosphorus Study
List of Figures

Figure 3-1 Temp./ DO profile, April 23, 2008 7
Figure 3-2 Temp./ DO profile, May 23, 2008 7
Figure 3-3 DO profile, June 11, 2008 7
Figure 3-4 DO profile June 27, 2008 7
Figure 3-5 DO profile, July 11, 2008 8
Figure 3-6 DO profile, August 20, 2008 8
Figure 3-7 DO profile, September 5, 2008 8
Figure 3-8 Temp./DO profile, October 8, 2008 8
Figure 3-9 Webster Lake Volume Distribution 10
Figure 3-10 Epilimnetic and Hypolimnetic phosphorus April-October, 2008 12
Figure 3-11 Temp./DO/ Chl-a profile, June 27, 2008 15
Figure 3-12 Temp./DO/ Chl-a profile, July 11, 2008. 15
Figure 3-13 Temp./DO/ Chl-a profile, July 17, 2008. 16
Figure 3-14 Temp./DO/ Chl-a profile, August 20, 2008 16
Figure 3-15 Temp./DO/ Chl-a profile, August 27, 2008.. 17
Figure 3-16 Temp./DO/ Chl-a profile, September 10, 2008 17
Figure 3-17 Temp./DO/ Chl-a profile, September 16, 2008 18
Figure 3-18 Temp./DO/ Chl-a profile, October 8, 2008. 18
Figure 3-19 Secchi Depth, 2008 19
Figure 3-20 Webster Lake Phytoplankton, Diatoms, 2008 20
Figure 3-21 Webster Lake Phytoplankton, Golden-browns, 2008 20
Figure 3-22 Webster Lake plankton, Cyanobacteria, 2008 21
Figure 3-23 Sucker Brook Total Phosphorus, May through October, 2008 22
Figure 3-24 Periphytic algal productivity in Sucker Brook, May 13, 2008. 23
Figure 4-1 Vollenweider, no internal phosphorus loading, yielding 12 ug/l. 26
Figure 4-2 Vollenweider, internal phosphorus loading 26
Figure 5-1 Phosphorus and Chlorophyll-a, April-October, 2008 28
Figure 5-2 Webster Lake Phytoplankton, Relative Abundance, 2008 29

Webster Lake Phosphorus Study
List of Tables

Table 1-1 Aquatic Life Use Nutrient Criteria by Trophic Class 2
Table 3-1 Upper and Lower Layer Phosphorus, Webster Lake, 2008 13

1.0 INTRODUCTION AND PURPOSE

1.1 Introduction

Every two years New Hampshire reports the water quality status of New Hampshire'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).

Section 305(b) of the CWA requires submittal of a report (commonly called the "305(b) Report"), that describes the quality of its 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 in 2009 (Trowbridge) are used to assess both the primary contact recreation (PCR) and the aquatic life (AL) uses 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 ALU 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 threshold exceeded	Impaired	Impaired	Impaired
Chl threshold not exceeded	Fully supporting	Fully supporting	Fully supporting
Insufficient information for Chl	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 exceedances 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 table 1-1 below.

Table 1-1: 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

Webster Lake, Franklin, New Hampshire, 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. Additionally, Webster Lake has been listed for aquatic life use impairment in 2010, for not meeting phosphorus and Chl-a criteria, since the 10 year median TP of 10 ug/L and Chl-a of 4.36 exceeds the criteria for oligotrophic lakes.

The impaired waterbody designation resulted in a DES funded EPA Section 319 NPS restoration grant to develop a watershed management plan. The Webster/ Highland Lake Watershed Management Plan (VHB, 2006) assisted with watershed planning and outlined potential best management practices to reduce phosphorus loading to Webster Lake. The WMP goals are to reduce cyanobacteria cell production, increase lake clarity and increase recreational use days. The decrease in cyanobacteria cell production and cyanotoxicty 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 limnology research. However, it is well documented that increased phosphorus and nitrogen 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 most likely to experience cyanobacteria dominance (Smith, 1983, 1990).

A goal of the Webster/Highland Lake Watershed Management Plan (WMP) is to provide methods that result in phosphorus load reductions that in turn limit primary productivity (Chl-a), including cyanobacteria. Phosphorus loading reductions through watershed management and hypolimnetic phosphorus inactivation was successful at Kezar Lake, North Sutton, New Hampshire (Connor and Martin, 1989). This successful lake restoration project demonstrated that substantial chlorophyll reductions, increased lake clarity, and elimination of cyanobacteria dominance to a natural succession of phytoplankton species occurred after watershed phosphorus loading was reduced and properly researched in-lake restorative efforts were achieved. Although Webster Lake is not currently impaired for chlorophyll-a, P load reductions both from the watershed and the lake will likely result in decreased chlorophyll-a concentration through reduced phytoplankton and cyanobacteria cell production.

Cyanobacteria surface scums are documented by DES Beach Program personnel during the swimming season (June through August) or though lakeshore owner complaints. The Webster Lake Cyanobacteria scums often occur in late summer and early fall, although the migration of Cyanobacteria through the water column typically occurs throughout August into mid-October. DES recently documented an increase of cyanobacteria cells clumped in the water column or in the form of surface scums on September 10, 2003 and August 27, 2007 and October 8, 2008.

Although Cyanobacteria blooms are observed and documented in late summer and fall once they rise to the surface, cell densities have periodically been documented by DES personnel in the lake at monitored depths for some time. Cyanobacteria cell densities and the resulting data show that lake temperature and hypolimnetic anoxia increased with summer progression, favoring internal phosphorus loading. Because of the simultaneous release and uptake within the sediments, documentation of internal P load rates are impossible to calculate but are estimated through mass balance equations, therefore the total mass of internal P loading is uncertain throughout the summer months. Limnological studies have shown phosphorus entrainment through stratified lakes, phosphorus mixing in weakly stratified lakes and total phosphorus mixing during fall turnover. It is not fully understood what influence internal loading has on Webster Lake overall in-lake phosphorus concentrations. Hypolimnetic data collected over the last 30 years lead limnologist to conclude that the high hypolimnetic phosphorus load to the lake likely has an impact on the Webster Lake water quality.

The Vollenweider Water Quality Model (Vollenweider, 1976) was utilized in the WMP to predict the influence of watershed phosphorus loading on lake quality. The Vollenweider model predicts in-lake phosphorus concentration following spring overturn during fully mixed conditions. The WMP based in-lake phosphorus concentration goals on the one, fully-mixed, in-lake phosphorus sample (15 ug/l) collected April 3, 2006 (6 meter tube composite). An additional fully-mixed phosphorus sample was collected on and April 26, 2007 (7 meter tube composite) and also measured 15 ug/l. These sample concentrations are 2-3 ug/l greater than mean summer (5 ug/l greater than the median summer) epilimnetic phosphorus concentration for Webster Lake.

The Vollenweider model predicts spring in-lake phosphorus concentrations based upon phosphorus loads from the watershed. As a result there is little emphasis on accounting for internal phosphorus loads which can have a substantial impact on water

quality as determined by primary productivity and cyanobacteria blooms. For the WMP, internal loads were estimated by multiplying the tendency of the summer mean hypolimnetic P concentrations (20-30 ug/l) by the volume of the hypolimnion to generate a P mass. If the hypolimnetic P mass is calculated based upon a hypolimnetic P concentration estimate that was too low, this could skew the internal load estimate and in-lake P concentrations lower indicating better water quality than actually exists and possibly not explain the presence of algal blooms, including cyanobacteria.

In retrospect, late summer or early fall hypolimnetic phosphorus samples could have potentially been used as the basis for estimating internal phosphorus loading since all Cyanobacteria scums were reported in late August through mid-October after several months of potential internal phosphorus loading. A goal of the WMP is to eliminate the water quality impairment, cyanobacteria scums. Since development of the WMP, Webster Lake has also been listed as impaired for aquatic life due to Chl-a and nutrient exceedences. A more thorough understanding of internal phosphorus loading and the potential impact to increased in-lake phosphorus concentration is necessary. Only through continued research will scientists understand the role of internal P loading and how it influences cyanobacteria and subsequent scum formation.

1.3 Purpose

The WMP established a fully-mixed, spring, in-lake phosphorus concentration goal of 11 to 12 ug/l. This is a 2-3 ug/l phosphorus load reduction from 15 ug/l, based upon a single spring, fully-mixed sample collected on April 3, 2006. The purpose of this study was to explore the following questions:

1) Does 15 ppb adequately represent fully mixed, spring in-lake phosphorus conditions?

2) How much internal loading occurs throughout the summer and fall?

3) What are the weekly lake phosphorus concentrations, April-October if hypolimnetic phosphorus from internal loading is considered to be fully-mixed throughout the lake?

4) How much internal phosphorus loading occurs prior to increased algal productivity as measured by decreased water clarity?

5) How much internal phosphorus loading occurs prior to a dominance of Cyanobacteria as measured by relative abundance?

6) How does accounting for internal loading impact predicted in-lake phosphorus concentrations developed by the Vollenweider model (1976).

7) How much internal phosphorus loading reduction is necessary to prevent increased algal and cyanobacteria cell production?

2.0 METHEDOLOGY

2.1 Webster Lake, in-lake

Weekly in-lake data was collected from Webster Lake of the following lake quality parameters:

1) Temperature, dissolved oxygen, specific conductance and chlorophyll a at the deep spot profile at either 0.5 or 1.0 meter intervals using a Hydrolab DataSonde 4.

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

3) Plankton haul (80 micron net) sample to determine plankton relative abundances. Two samples were collected; one corresponding with the Chl-a sample depth, and one from 0-10 meters.

4) Discrete Total Phosphorus samples; 3 meters, representing epilimnetic and metalimnetic phosphorus concentrations and 10 meters, representing hypolimnetic phosphorus concentration.

5) Secchi Disk Depth to measure lake clarity.

6) Lake elevation was recorded weekly from April-October, using a permanent staff gage maintained by the DES Dam Bureau. No water quality samples were collected at the outlet.

2.2 Sucker Brook

Weekly TP samples and staff gage measurements were collected from Sucker Brook to provide a broad loading estimate for comparison to previous studies, by Dufresne-Henry (1981) and NHDES (1990) to compare recent Sucker Brook phosphorus loading data to past P loading studies. The Sucker Brook TP loading estimate (Dufresne-Henry Study, 1981) was referenced in the 2006 WMP.

3.0 STUDY DATA

Webster Lake in-lake data was collected on a weekly basis, beginning at ice out in late April, 2008 until 1-2 weeks after lake drawdown in early fall, 2008. The following sections discuss data collected for temperature and dissolved oxygen profiles, phosphorus, Chlorophyll-a profiles, secchi depth and relative plankton abundance.

3.1 Temperature/ Dissolved Oxygen

Temperature/ DO profiles were collected weekly, beginning April 23, 2008. Figure 3-1, demonstrates thermal stratification was initiated when water temperatures measured between 4ºC and 7 ºC. Oxygen concentrations were greater than 4 mg/l, or 30 percent saturation throughout the April profile. Instrumentation failure prevented temperature/ DO profile collection on April 30 and May 7, 2008. By May 23, 2008, lake temperatures were well stratified as seen in figure 3-2. Hypolimnetic dissolved oxygen

concentration gradually decreased throughout the month of June. Between July 11, 2008 and September 5, 2008, low hypolimnetic dissolved oxygen concentrations (less than 3 percent) expanded with increased depth. In July, low dissolved oxygen was measured in the bottom three meters. In August, the bottom four meters had low dissolved oxygen concentrations. By early September, the bottom five meters experienced oxygen depletion. See figures 3-3 through 3-7 for dissolved oxygen profiles. Starting in October, temperature stratification began to weaken with isothermal conditions present by October 8, 2008. This is shown in figure 3-8.

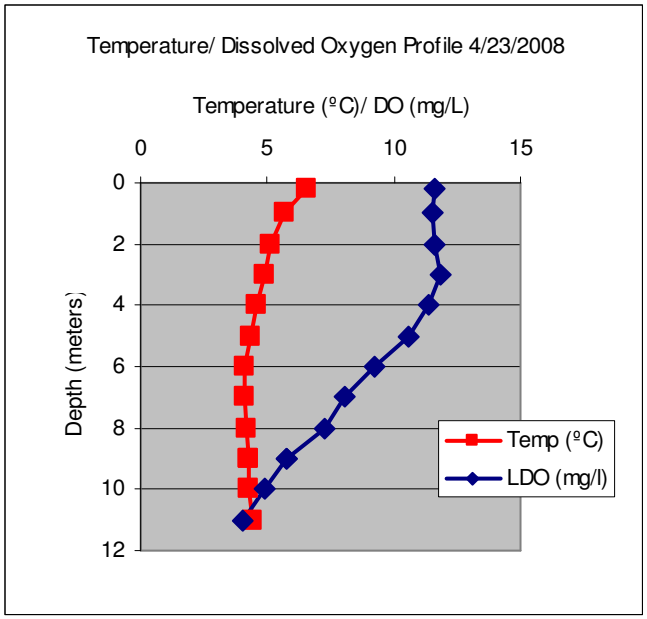


Figure 3-1: Temp/ DO profile, April 23, 2008

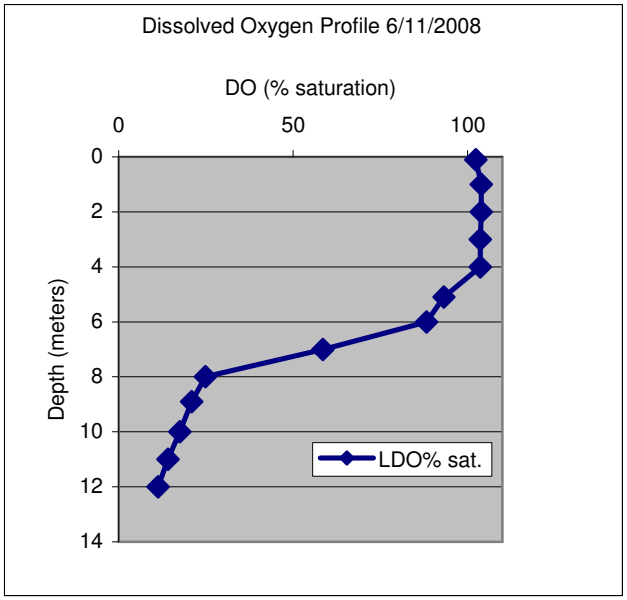


Figure 3-3: DO profile, June 11, 2008

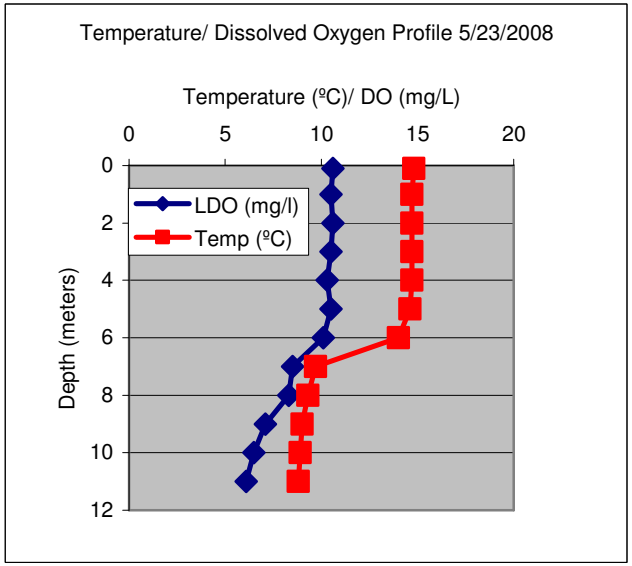


Figure 3-2: Temp./ DO profile, May 23, 2008

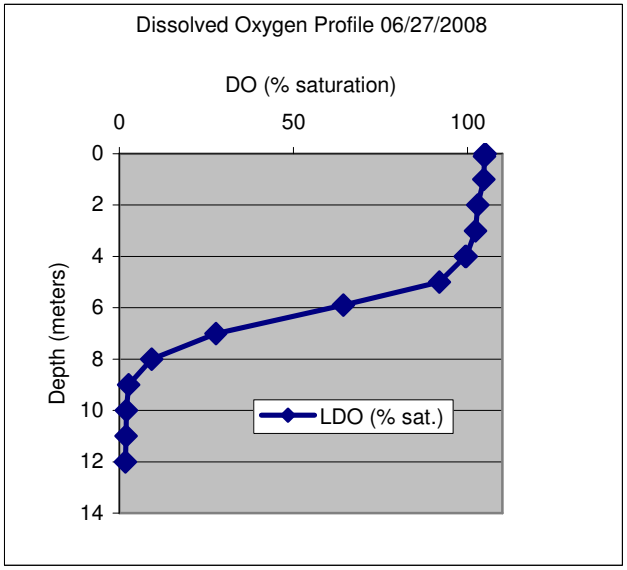


Figure 3-4: DO profile June 27, 2008

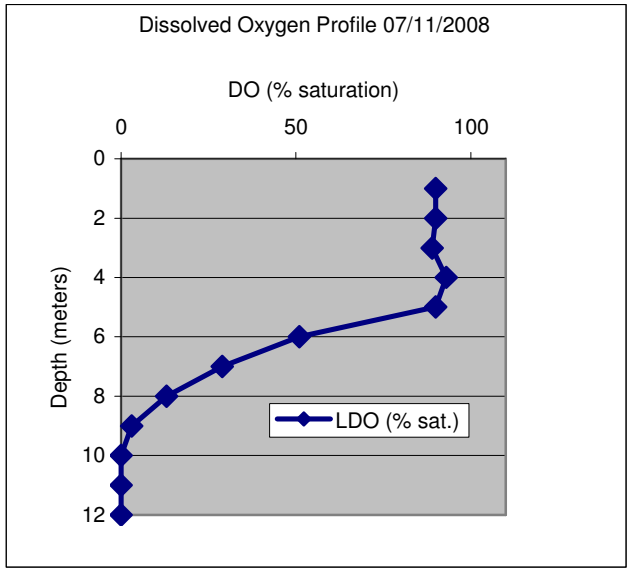


Figure 3-5: DO profile, July 11, 2008

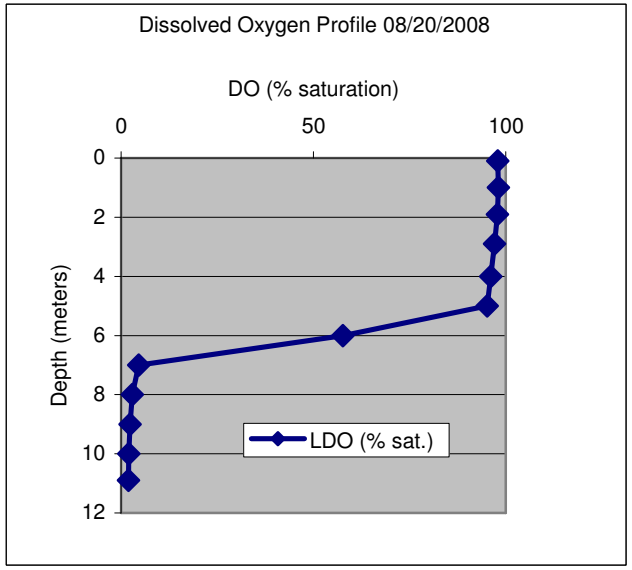


Figure 3-6: DO profile, August 20, 2008

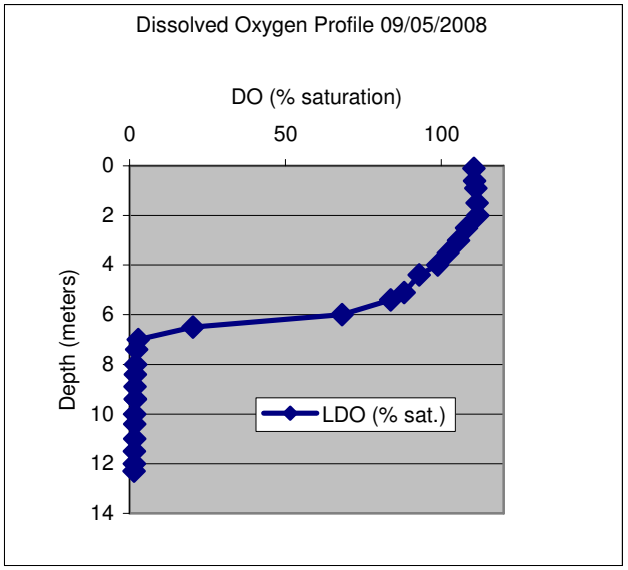


Figure 3-7: DO profile, September 5, 2008

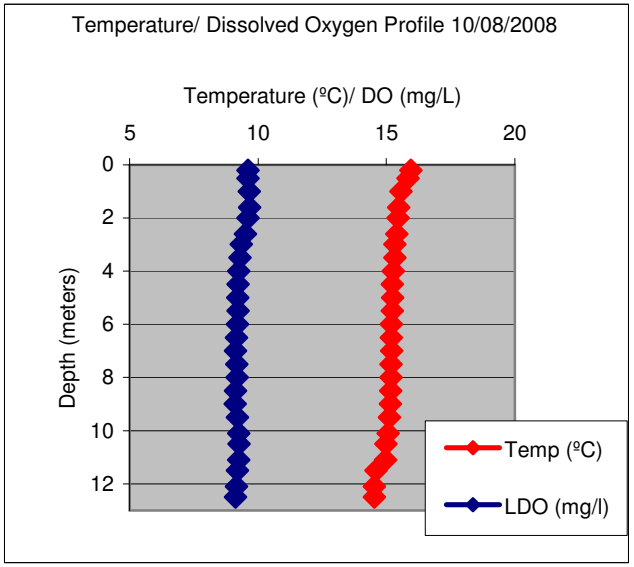


Figure 3-8: Temp/DO profile, October 8, 2008

3.2 Phosphorus

Total Phosphorus (P) samples were collected weekly at 3 meters (epilimnion) and at 10 meters (hypolimnion) beginning April 23, 2008 and ending October 22, 2008. Figure 3-10 provides the P data from April through October.

The total lake volume based on historical bathymetry is estimated at approximately 452 million cubic feet. In 2009, the Webster Lake bathymetry was recreated (Appendix A) to provide improved volumetric data and revised upwards to 459 million cubic feet. According to the summer temperature/ dissolved oxygen profiles, well oxygenated upper waters extend from 0 to 8 meters while oxygen depleted waters extend from 8 meters to the lake bottom, approximately 13.5 meters.

P concentration and equivalent P loads were steady from April through mid-June in both the upper and lower water layers. Beginning in late-June, internal P loading was measured in the hypolimnion, more than doubling the in-lake hypolimnetic P concentration typically found between April and June. P concentrations increased in the epilimnion by mid-August as the P concentration approached 15 ug/l; a 3-8 ug/l increase from P concentrations measured in April through July.

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

For lakes with anoxia that is fully contained in the hypolimnion, internal P loads are easily calculated, assuming the hypolimnetic P concentration is uniform, by multiplying the hypolimnetic P concentration by the hypolimnetic lake volume. However, this is not the case with Webster Lake as anoxic conditions are present in the metalimnion from early-August through September. As a result, the hypolimnetic P mass does not remain in the hypolimnion and is instead biologically uptaken by algae, including cyanobacteria at the hypolimnion-metalimnion interface and possibly by other algae within the metalimnion.

To estimate the P load representative of internal P loading, P mass for the lake layers receiving internal P loads must be calculated. To simplify the model, it was assumed that: 1) the anoxic hypolimnetic volume is below 8 meters as derived from profile data, 2) the epilimnetic/ metalimnetic volume that receives internal P loads is directly above the 8 meter depth plane since internal P loads are generated below 8 meters, 3) internal P loads transported to the metalimnion/ epilimnion is evenly distributed throughout that volume, and 4) There is no horizontal movement of internal P loads in the epilimnion/ metalimnion where lake depths are less than 8 meters.

P mass values were extrapolated by multiplying P concentration by the associated depth zone volume; either the 0-8 meter depth volume directly over the 8 meter depth plane (volume B), representing the epilimnion and metalimnion receiving internal P loads or 8-13.5 meter depth volume (volume C) to represent the hypolimnion. Volume A is the remaining volume in the epilimnion and hypolimnion that is assumed to receive no internal P loads prior to destratification. P mass for Volume A was calculated by multiplying epilimnetic P concentration by volume through July 23, 2008. After July 23, 2008, P mass for volume A was calculated by multiplying the mean epilimnetic P concentration (0.0096 mg/l from April 23,-July 23, 2008) by volume.

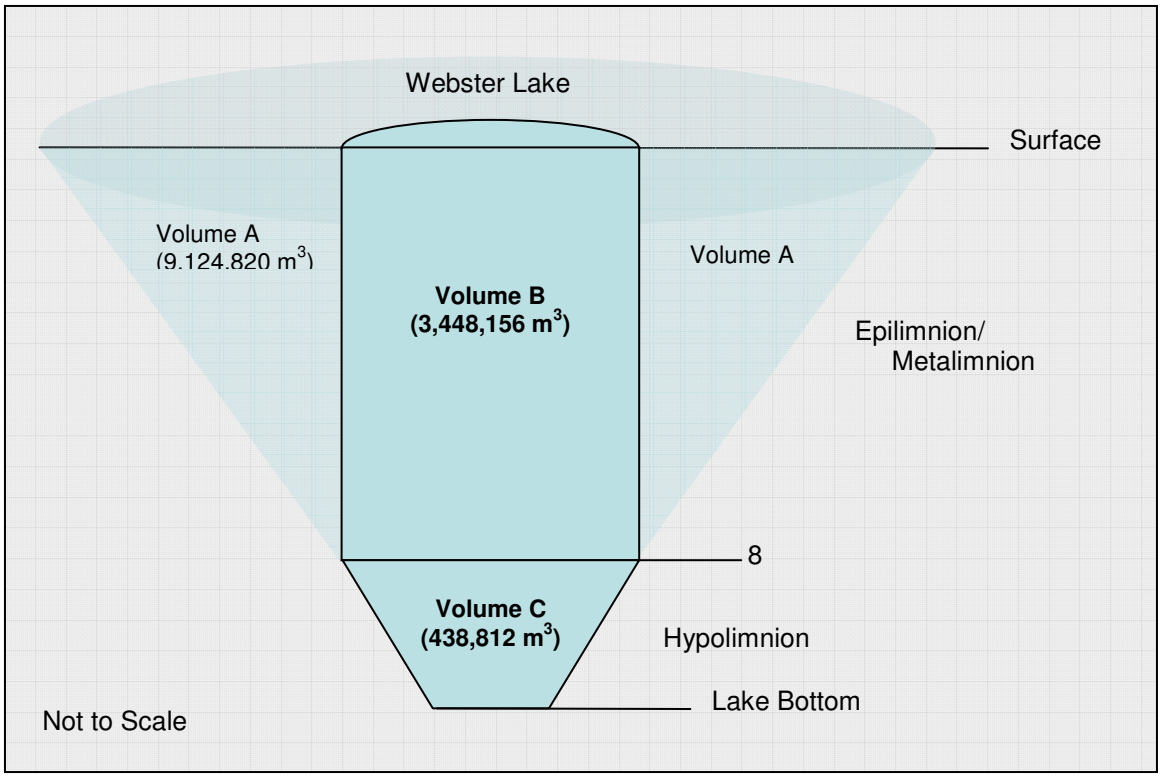


Figure 3-9: Webster Lake Volume Distribution

To determine the P load representative of internal P loading in the hypolimnion, a baseline P mass value for hypolimnion was established. From April 23, 2008 through June 18, 2008, the average hypolimnetic P mass during that time was 9.6 kg. Any increase in hypolimnetic P mass after June 18, 2008 was considered to be the result of internal P loads since there was a substantial increase in hypolimnetic P concentration from 26 ug/l to 42 ug/l from June 18, 2010 to July 9, 2008. From June 27, 2008 through July 30, 2008, internal P loading was contained within the hypolimnion. On August 6, 2008, anoxic conditions approached the thermocline. At that time, the P mass in the hypolimnion was 36.9 kg, yielding an internal P load of 27.3 kg (36.9 kg – 9.6 kg).

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. From April 23, 2008 through July 30, 2008, the average epilimnetic/ metalimnetic P mass directly over the 8 meter depth plane equaled 32.4 kg. Any increase in epilimnetic/ metalimnetic P mass after July 30, 2008, either transported from the hypolimnion or from the sediments of the anoxic metalimnion were assumed to be internal P loads present in the metalimnion/ epilimnion. This was supported by a steady P concentration increase at the deep spot epilimnion for several weeks after July 30, 2008. On August 6, 2008 the internal P mass in Volume B of the epilimnion/ metalimnion was 37.9, yielding a total internal P load of 5.6 kg in the epilimnion/ metalimnion and in total, a 32.4 kg internal P load for Webster Lake.

As the summer and anoxic lake conditions progressed, P loads resulting from internal loading increased. On September 16, 2008, a maximum internal P load of 84.4 kg existed in Webster Lake. See table 3-1.

It should also be noted there are several shortcomings to this modeling approach, mainly due to a lack of P data, particularly within the metalimnion throughout the sampling season, but also a lack of P data in other parts of the lake or fluid dynamics modeling which would have yielded a better understanding of the distribution of internal P loads throughout the lake system.

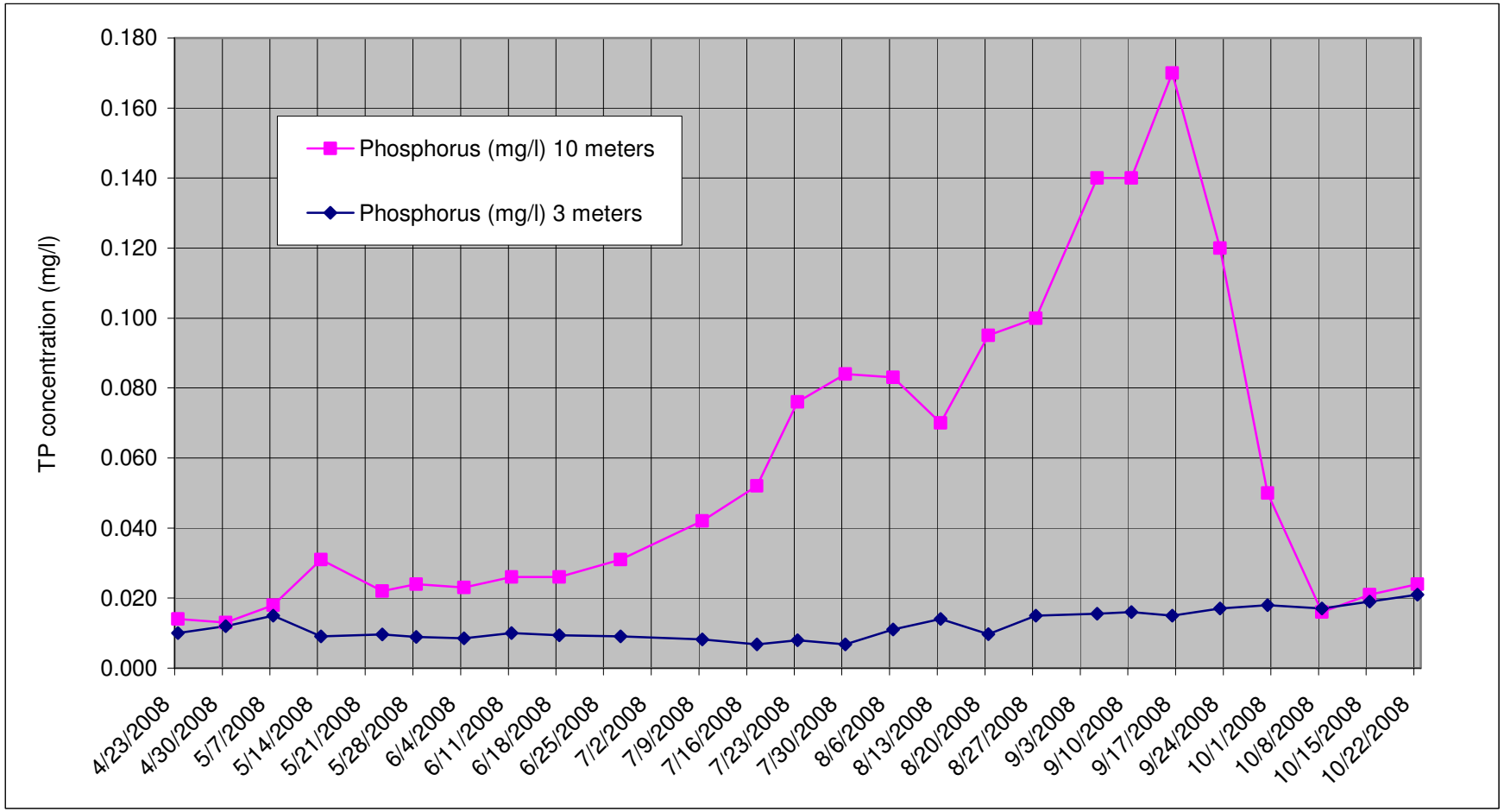


Figure 3-10: Epilimnetic and Hypolimnetic phosphorus concentrations April-October, 2008.

Table 3-1: A comparison of phosphorus mass and concentration in the upper (Epi/Meta) and lower (Hypo) layers of Webster Lake

Date	Phosphorus (mg/l) 3 meters [over hypo, 8-13.5 meters]	Epi./Meta. Phosphorus [1] (kg) [over hypo 8-13.5 meters]	Phosphorus (mg/l) [not over hypo, 8-13.5 meters]	Epi./Meta. Phosphorus [1] (kg) [not over hypo 8-13.5 meters]	Phosphorus (mg/l) 10 meters	Hypo. Phosphorus [1] (kg)	Total Phosphorus Load (kg)	Volume weighted lake P concentration (mg/l)	Internal P load (kg) post 6/18/10 remaining in Hypo.	Internal P load (kg) post 7/30/10 transported to Meta/Epi (anoxia within thermocline)	Weekly Total Internal P load (kg) in lake
4/23/2008	0.0100	34.5	0.0100	91.2482	0.0140	6.1	131.87	0.0101			
4/30/2008	0.0120	41.4	0.0120	109.4978	0.0130	5.7	156.58	0.0120			
5/7/2008	0.0150	51.7	0.0150	136.8723	0.0180	7.9	196.49	0.0151			
5/14/2008	0.0091	31.4	0.0091	83.0359	0.0310	13.6	128.02	0.0098			
5/23/2008	0.0096	33.1	0.0096	87.5983	0.0220	9.7	130.35	0.0100			
5/28/2008	0.0089	30.7	0.0089	81.2109	0.0240	10.5	122.43	0.0094			
6/4/2008	0.0085	29.3	0.0085	77.5610	0.0230	10.1	116.96	0.0090			
6/11/2008	0.0100	34.5	0.0100	91.2482	0.0260	11.4	137.14	0.0105			
6/18/2008	0.0094	32.4	0.0094	85.7733	0.0260	11.4	129.60	0.0100			
6/27/2008	0.0091	31.4	0.0091	83.0359	0.0310	13.6	128.02	0.0098	4.0		4.0
7/9/2008	0.0082	28.3	0.0082	74.8235	0.0420	18.4	121.53	0.0093	8.8		8.8
7/17/2008	0.0068	23.4	0.0068	62.0488	0.0520	22.8	108.31	0.0083	13.2		13.2
7/23/2008	0.0080	27.6	0.0080	72.9986	0.0760	33.3	133.93	0.0103	23.7		23.7
7/30/2008	0.0068	23.4	0.0096	87.4579	0.0840	36.9	147.77	0.0114	27.3		27.3
8/6/2008	0.0110	37.9	0.0096	87.4579	0.0830	36.4	161.81	0.0124	26.8	5.6	32.4
8/13/2008	0.0140	48.3	0.0096	87.4579	0.0700	30.7	166.45	0.0128	21.1	15.9	37.0
8/20/2008	0.0097	33.4	0.0096	87.4579	0.0950	41.7	162.59	0.0125	32.1	1.1	33.2
8/27/2008	0.0150	51.7	0.0096	87.4579	0.1000	43.9	183.06	0.0141	34.3	19.4	53.6
9/5/2008	0.0155	53.4	0.0096	87.4579	0.1400	61.4	202.34	0.0156	51.8	21.1	72.9
9/10/2008	0.0160	55.2	0.0096	87.4579	0.1400	61.4	204.06	0.0157	51.8	22.8	74.6
9/16/2008	0.0150	51.7	0.0096	87.4579	0.1700	74.6	213.78	0.0164	65.0	19.4	84.4
9/23/2008	0.0170	58.6	0.0096	87.4579	0.1200	52.7	198.73	0.0153	43.1	26.3	69.3
9/30/2008	0.0180	62.1	0.0096	87.4579	0.0500	21.9	171.47	0.0132	12.3	29.7	42.0
10/8/2008	0.0170	58.6	0.0096	87.4579	0.0160	7.0	153.10	0.0118	destratified		
10/15/2008	0.0190	65.5	0.0096	87.4579	0.0210	9.2	162.19	0.0125	destratified		
10/22/2008	0.0210	72.4	0.0096	87.4579	0.0240	10.5	170.40	0.0131	destratified		

[1] Calculated based upon 2009 bathymetry data. Epilimnion/Metalimnion volume directly over 8 meter depth plane = 3,448,156,523 liters. Epilimnion/ Metalinion volume not directly over 8 meter depth = 9,124,820,339 liters. Hypolimnion depth = 438,812,446 liters. Total lake vol. = 13,011,789, 308 liters.

3.3 Chlorophyll-a

Chlorophyll-a concentration is a measure of the green photosynthetic pigment in phytoplankton and cyanobacteria cells. Measuring chlorophyll-a, provides biologists with an indication of lake productivity through phytoplanktonic cellular concentration in the water column at any given time. Chlorophyll-a composite samples are typically collected as whole water samples from the water column where light-dependent algal productivity typically occurs, from the surface to the metalimnion. In addition to collecting chlorophyll-a composite samples, chlorophyll-a measurements were recorded at 1 meter increments from the surface to approximately 12 meters using a Turner fluorescent chlorophyll-a probe to develop chlorophyll-a profiles. The purpose of collecting chlorophyll-a data at each meter increment was to identify potential cyanobacteria layers migrating from the hypolimnion to the metalimnion and epilimnion prior to scum formation on the lake's surface.

Most of the chlorophyll-a profile data indicates maximum chlorophyll-a concentration around 10 ug/l (mg/m^3) and rarely exceeding 15 ug/l. Algal and/or cyanobacteria densities as measured by chlorophyll-a concentration were greatest within the metalimnion on most sampling days. Two exceptions to this were observed in early-mid July and late August through September. This may be the result from one or more of the following; planktonic cell die-off and settling, increased planktonic growth and resulting densities, or cyanobacteria movement within the water column.

Chlorophyll-a concentrations reached their greatest concentrations in the mid-metalimnion during late May through June. The following three profiles, figures 3-11 through 3-13, beginning in late June through the second week of July show a shift in chlorophyll-a concentrations from the metalimnion to lower-metalimnion/ hypolimnion.

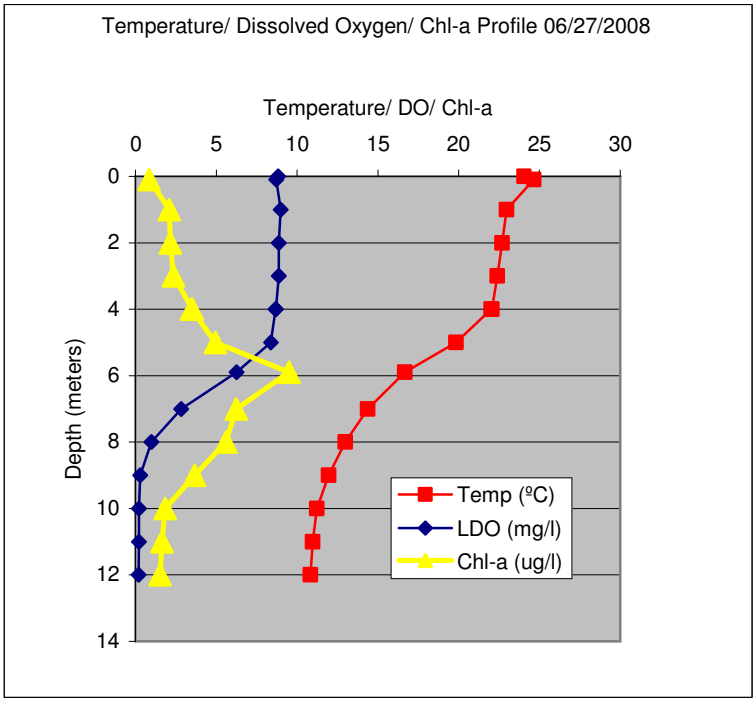


Figure 3-11: Temp./DO/ Chl-a profile, June 27, 2008.

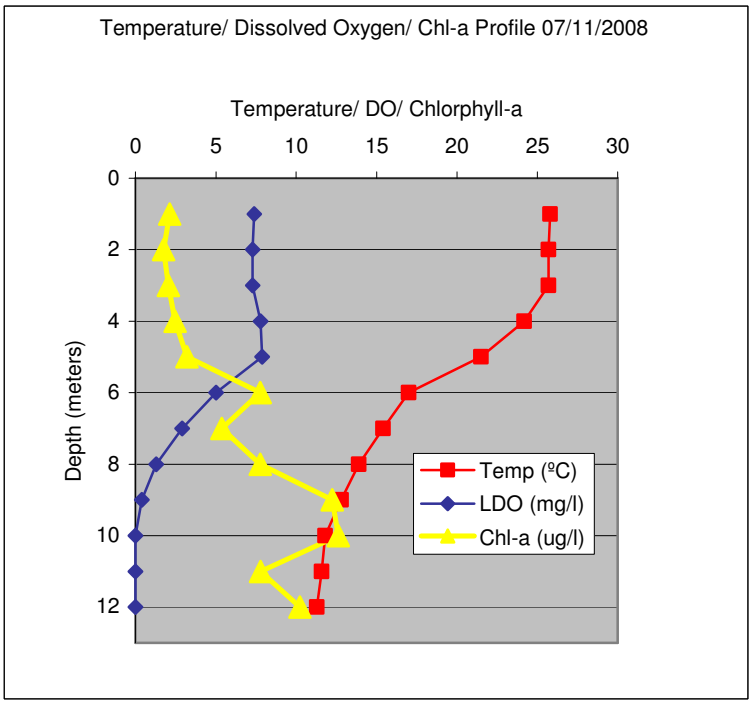


Figure 3-12: Temp./DO/ Chl-a profile, July 11, 2008.

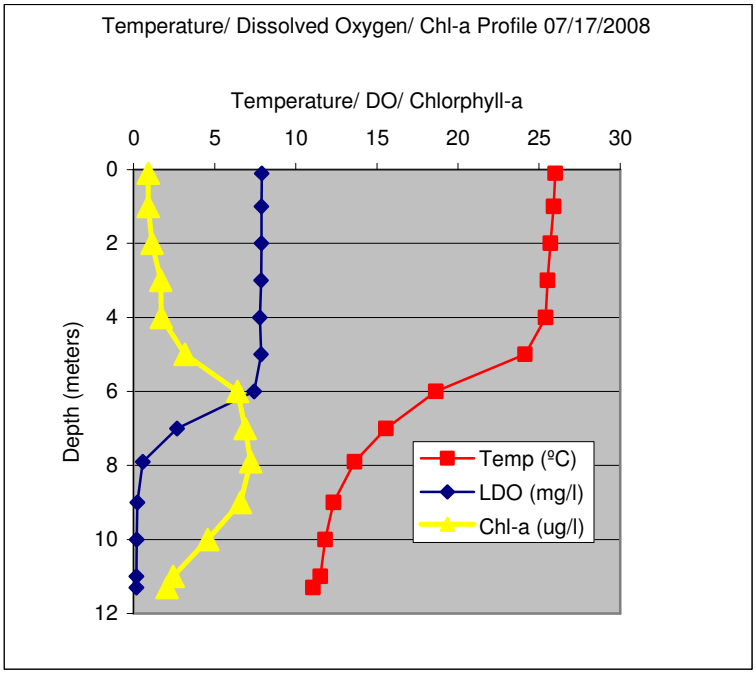


Figure 3-13: Temp./DO/ Chl-a profile, July 17, 2008.

Beginning in late August through September the chlorophyll-a concentrations continued to shift. The August 20, 2008, chlorophyll-a concentration (figure 3-14) was fairly uniform throughout the water column, ranging 2.6 ug/l to 7.6 ug/l.

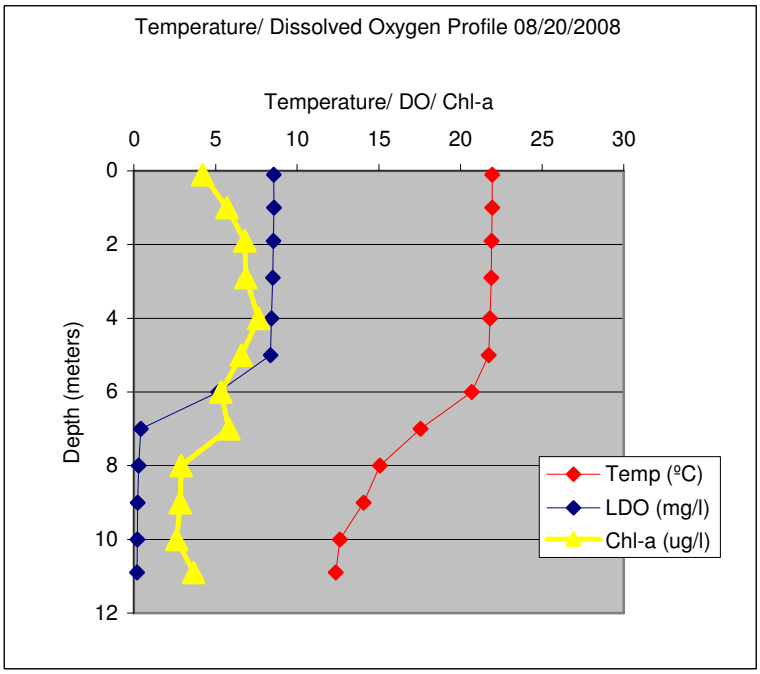


Figure 3-14: Temp./DO/ Chl-a profile, August 20, 2008.

Figures 3-15 through 3-18 demonstrates that Chlorophyll-a concentration increased throughout the epilimnion in comparison with previous sampling dates as algal production dominated the upper meters of the epilimnion until water temperature showed isothermal conditions in early October (figure 3-18). At this time hypolimnetic P became fully mixed resulting in increased algal productivity throughout the water column.

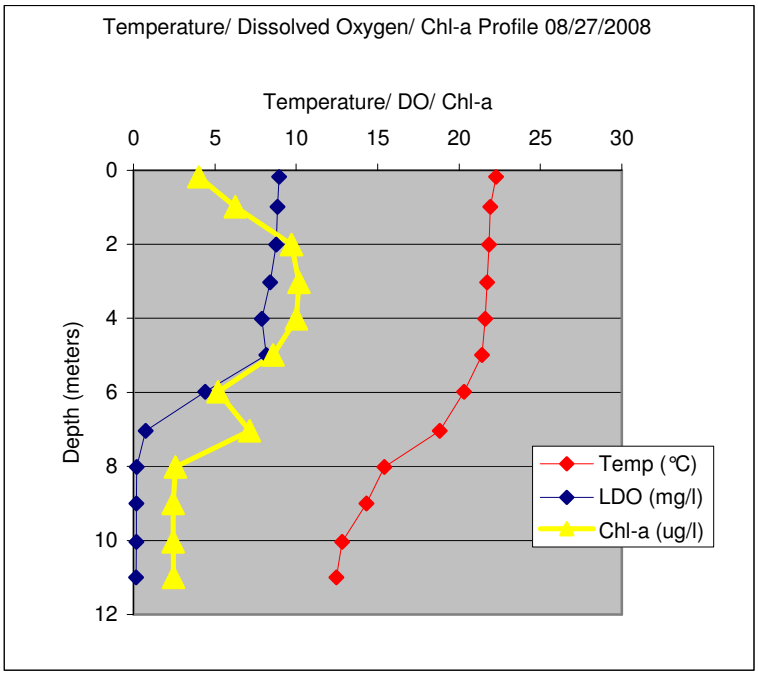


Figure 3-15: Temp./DO/Chl-a profile, August 27, 2008.

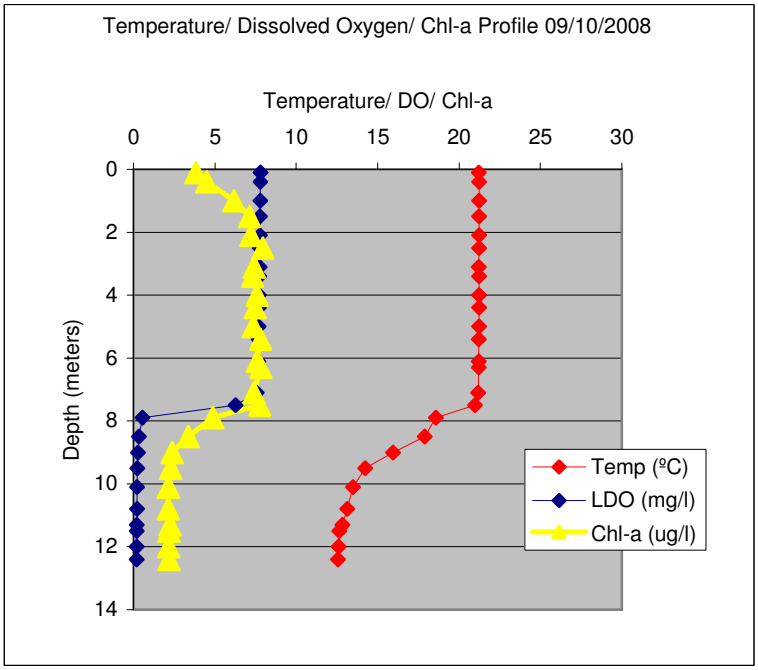


Figure 3-16: Temp./DO/Chl-a profile, September 10, 2008.

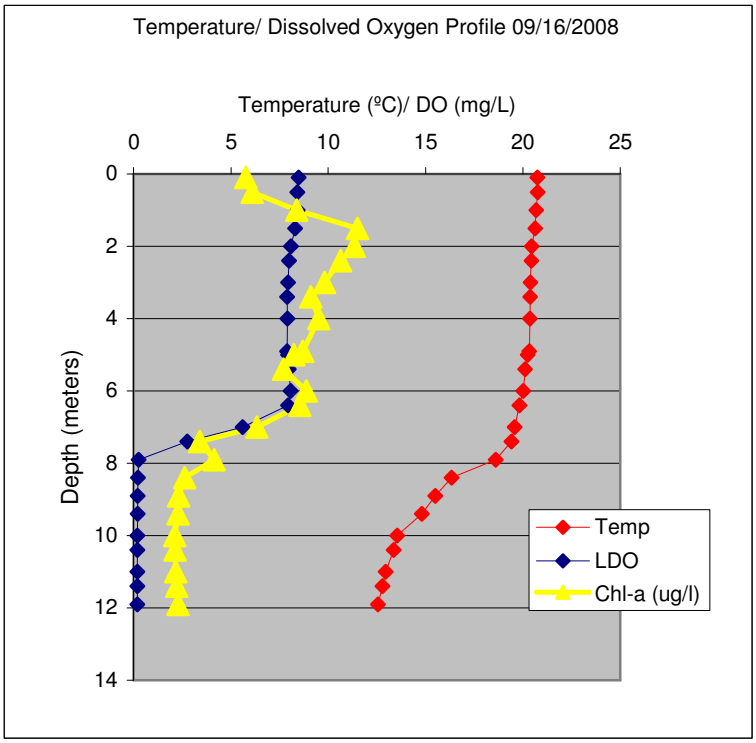


Figure 3-17: Temp./DO/Chl-a profile, September 16, 2008.

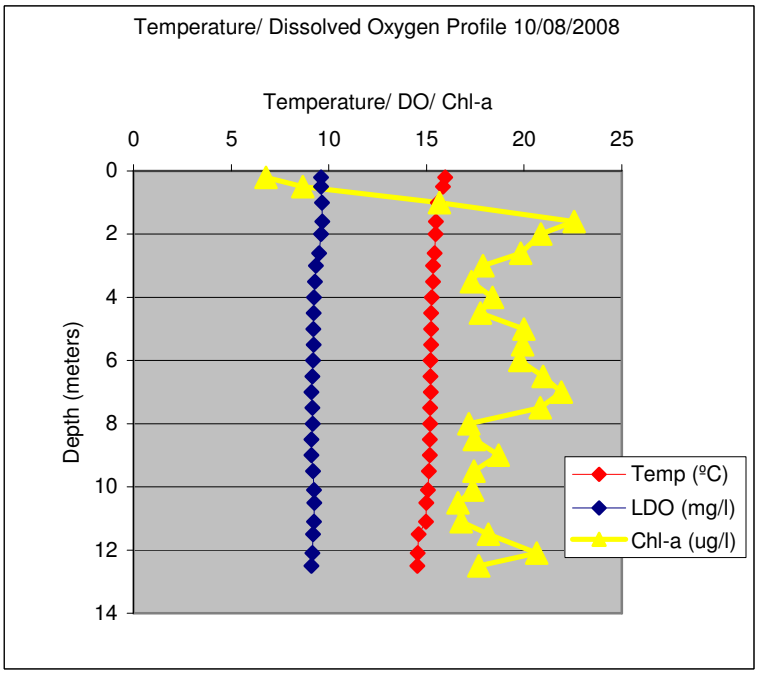


Figure 3-18: Temp./DO/Chl-a profile, October 8, 2008.

3.4 Secchi Depth

Secchi depth measurements were recorded on a weekly basis from April through October. During the early summer months, secchi depth varied between 3 and 5 meters, averaging approximately 3.93 meters. Between August 5, 2008 and August 12, 2008, clarity was greatly reduced due to increased algal productivity from the surface through mid-metalimnion. As shown in figure 3-19, from August 12, 2008 through October 22, 2008, average secchi depth clarity decreased to 2.40 meters. This is the result of increased algal densities that increased in late July through October.

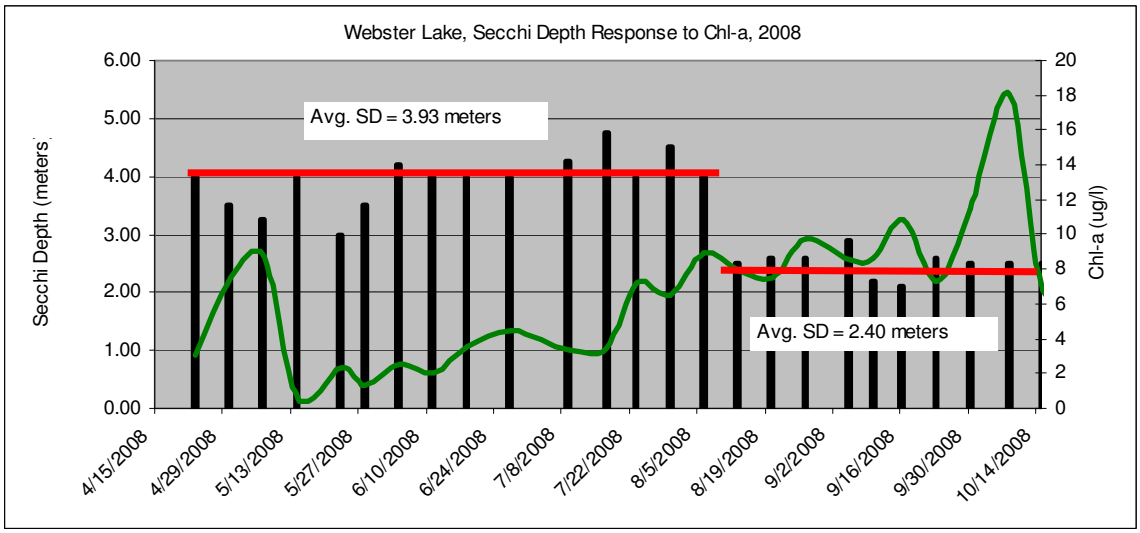


Figure 3-19: Secchi Depth, 2008

3.5 Plankton

Two 80 micron plankton net samples were collected on a weekly basis; one 10 meter vertical haul and one mid-metalimnion vertical haul. The following three figures provide relative abundance details for three phytoplankton categories, diatoms, golden-brown and cyanobacteria.

Diatoms dominated plankton samples throughout the season, with relative abundance of *Asterionella, Rhizosolenia* and *Tabellaria* often greater than 50 percent of the total cell population. *Synura*, a golden-brown, and *Anabaena*, a cyanobacteria reached relative abundances greater than 50 percent during several sampling events from July through October.

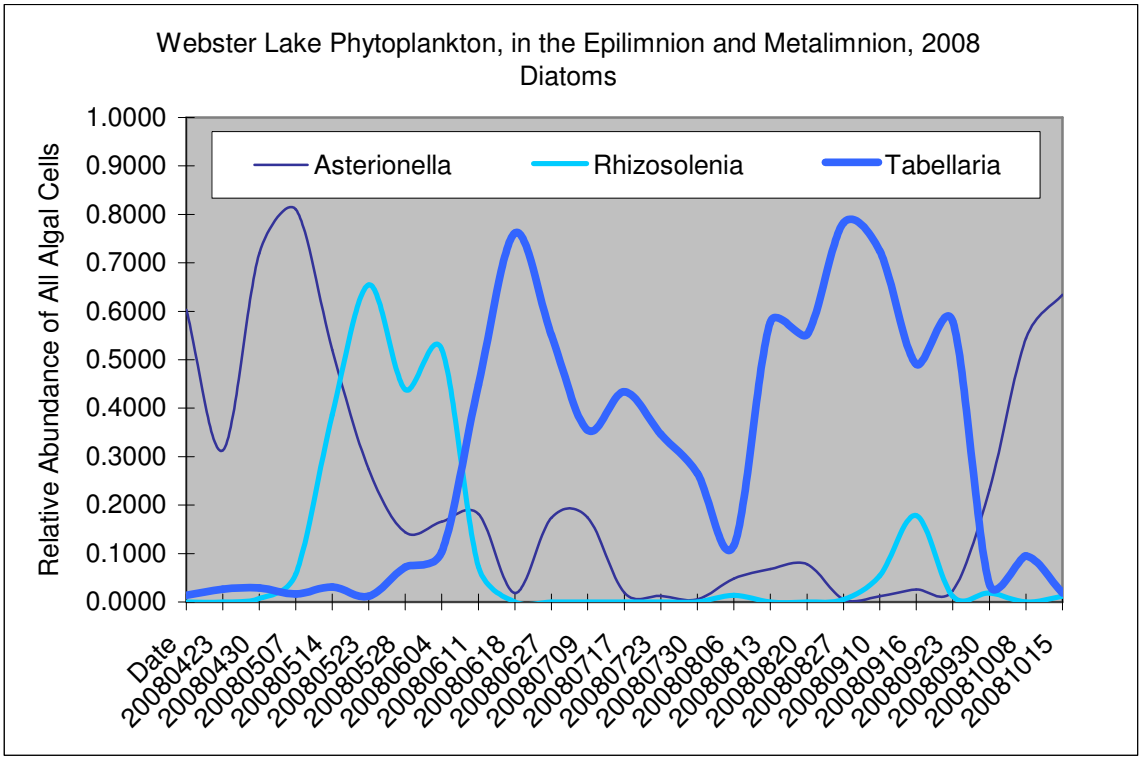


Figure 3-20: Webster Lake Phytoplankton Succession, Diatoms, 2008

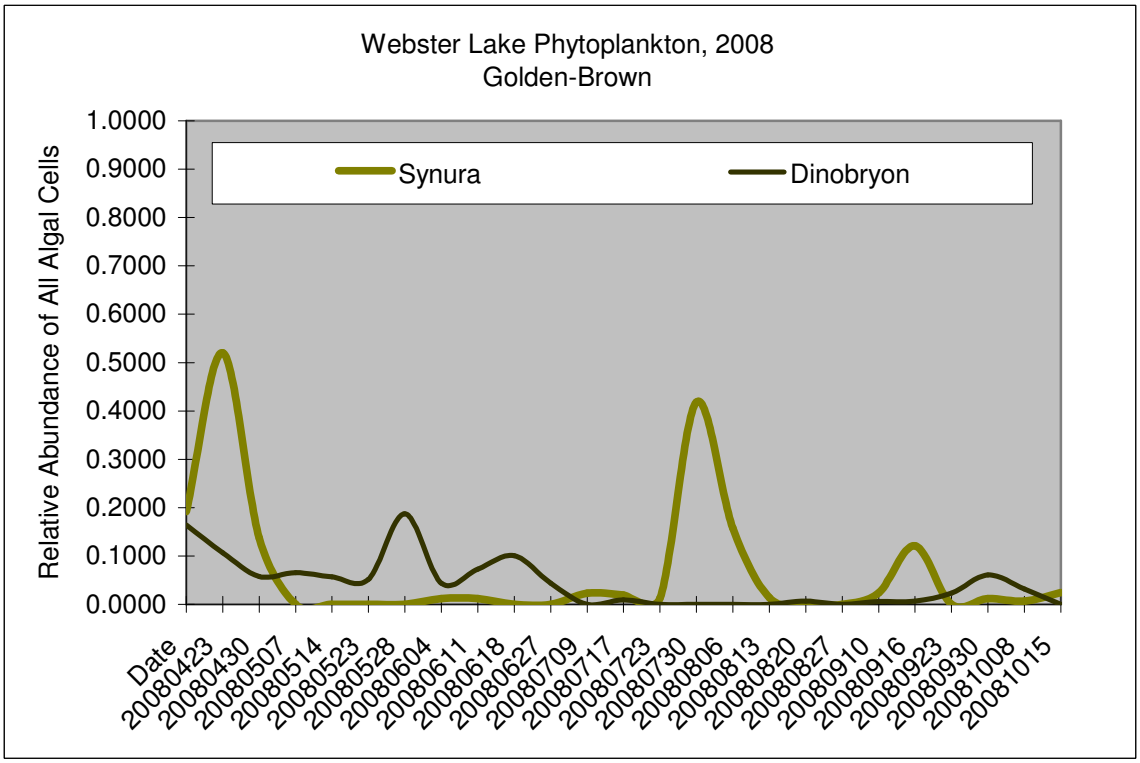


Figure 3-21: Webster Lake Phytoplankton Succession, Golden-browns, 2008

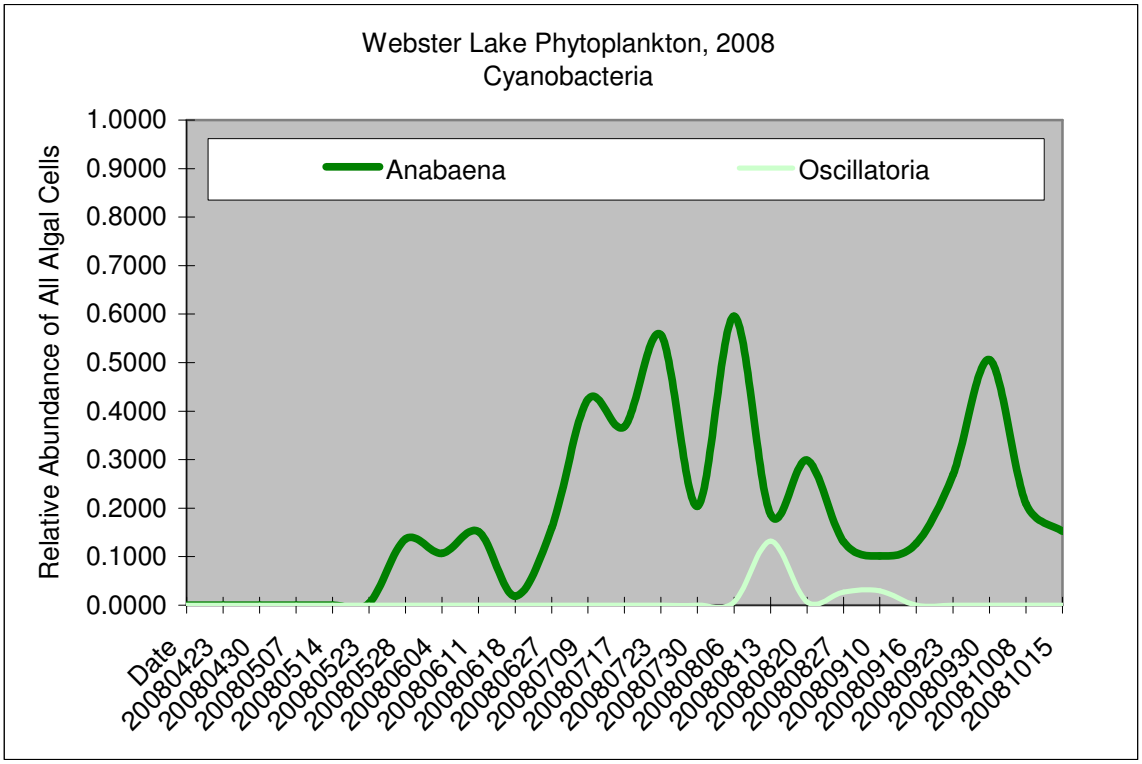


Figure 3-22: Webster Lake plankton Succession, Cyanobacteria, 2008

3.6 Sucker Brook

Sucker Brook is the largest hydrologic contributor tributary to Webster Lake. Its watershed includes Highland Lake, which encompasses approximately 80 percent of the entire Webster Lake watershed. The Dufrense-Henry Study (1981) estimated that Sucker Brook accounted for 63 percent (391 kg) of the total annual phosphorus load to the lake. The DES Study (1990) estimated that Sucker Brook accounted for 61 percent (265 kg) of the total annual phosphorus load to the lake. Phosphorus sampling and staff gage measurements for Sucker Brook occurred on a weekly basis from May through October during the 2008 season. Figure 3-23 provides phosphorus concentration and extrapolated daily loads. Daily loads were generally 0.4 to 1 kg P and no greater than 6 kg P with the exception of June 11, 2008 (10 kg P). If daily loads between 0.4 to 1.0 kg P are carried out to estimate annual loads, this would yield 146 to 365 kg P, respectively. The high-end estimate is slightly less than that estimated from the 1981 Dufresne-Henry Study discussed above. Further study may be necessary to investigate the cause of elevated P discharges from Sucker Brook in early June to determine if this was a one-time or routine occurrence, seasonal or otherwise.

Periphytic planktonic growth pictured in figure 3-24 was observed on rocks in the Sucker Brook streambed in early May, indicating an ample supply of sunlight and phosphorus in April, prior to sample collection. Light penetration through the spring canopy, prior to full leaf-out, typically accelerate periphytic growth along shallow tributaries.

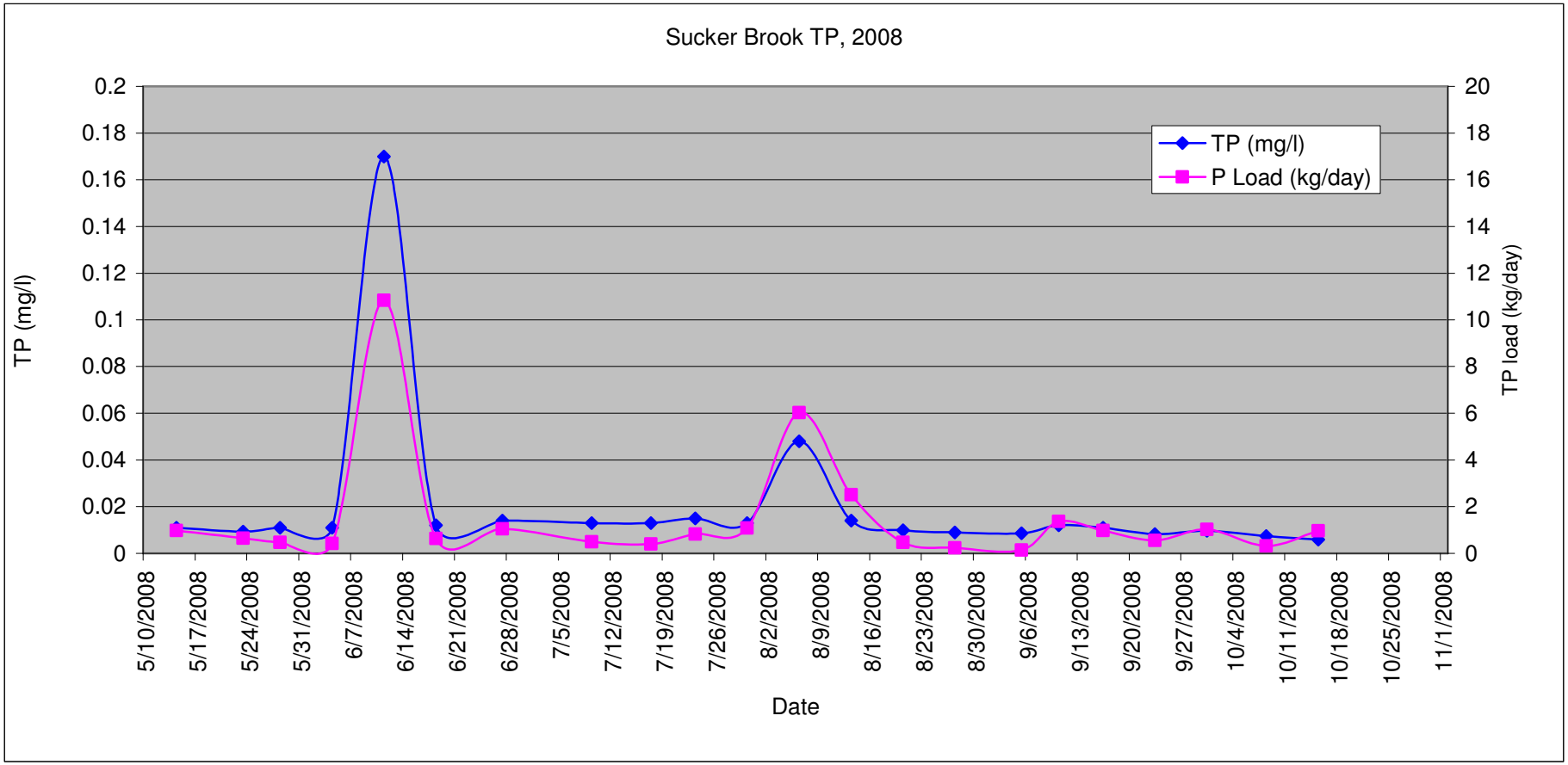


Figure 3-23: Sucker Brook TP concentrations and extrapolated daily loads May through October, 2008.

Figure 3-24: Periphytic algal productivity in Sucker Brook, May 13, 2008.

4.0 STUDY PURPOSE FINDINGS

Spring, non-stratified in-lake phosphorus concentration

A comparison of sample results from the 2008 Webster Lake monitoring program to samples previously collected in April, 2006 and April, 2007, reveal that 15 ug/l, the reference concentration for the watershed management plan, may overestimate the fully mixed, spring, in-lake phosphorus conditions. The late-April, 2008 in-lake phosphorus concentrations measured on April 23rd and 30th averaged 12 – 12.5 ug/l. However, phosphorus samples collected every three meters throughout the water column on April 20, 2009 varied between 17 and 26 ug/l and a mean P concentration of 21 ug/l. Spring P concentrations from 2006 to 2009 varied between 12 and 21 ug/l, indicating that substantial variability occurs between years and throughout the water column during the 2-3 week pre-stratification period. Therefore, 15-16 ug/l is considered an adequate representation of fully-mixed, spring in-lake phosphorus conditions. However, additional long-term watershed phosphorus load and in-lake phosphorus data sets that include early spring turnover would be useful to refine this number and to explain the variability.

Internal phosphorus loading estimates throughout the summer, 2008

The total hypolimnetic P mass can be defined as the sum of internal P loading and P transport to the hypolimnion from the epilimnion and metalimnion, less any P transport from the hypolimnion. The total hypolimnetic P mass can be estimated by multiplying the hypolimnetic phosphorus concentration by the hypolimnetic volume. Internal phosphorus loading occurs when benthic sediments release phosphorus to the sediment/water interface as a result of the disassociation of chemical bonds initiated through anoxic hypolimnetic waters. Assuming that P transport from the epilimnion and metalimnion to the hypolimnion is minimal, the increase in hypolimnetic P mass is substantially a result of internal P loading. Phosphorus concentration increases during anoxic hypolimnetic conditions can be attributed to internal loading, invertebrate migration and mixing during weakly stratified conditions. The total internal P loading throughout the season can be estimated by subtracting hypolimnetic pre-anoxic phosphorus mass from hypolimnetic anoxic phosphorus mass. Webster Lake anoxic conditions began the week after the June 18, 2008 sample date. The average hypolimnetic P mass from April 23, 2008 through June 18, 2008 of 9.6 kg P is used as the benchmark for pre-anoxic phosphorus loads for the 2008 sampling season.

Oxygen concentration gradually decreased in the hypolimnion through mid-June and hypolimnetic phosphorus concentrations were relatively stable, measuring between 22 and 26 ug/l for several weeks ending June 18, 2008. The June 18, 2008 hypolimnetic phosphorus mass estimate was 11.4 kg (table 3-1), the hypolimnetic waters were oxygenated, and indicating the P loading was natural rather than internal. However, by the end of July, anoxic conditions existed below 8 meters resulting in a hypolimnetic phosphorus mass of approximately 36.9 kg, yielding a corresponding internal load of 27.3 kg P (36.9 kg P – 9.6 kg P). By mid September, the hypolimnetic phosphorus mass equaled 74.6 kg, yielding an internal load of approximately 65.0 kg P (74.6 kg P – 9.6 kg P).

As stated above, assuming that P transport into and out of the hypolimnion is minimal, much of the internal loading remains in the hypolimnion. As the summer progressed and phosphorus concentrations increase with depth, phosphorus concentrations at the metalimnion/anoxic zone interface also increased. Plankton phosphorus uptake on the thermocline shelf and lysing of planktonic cells results in increased phosphorus concentrations to the surface as upper waters mix. This is evident in table 3-1. Epilimnetic/ metalimnetic mean phosphorus concentrations increased from 8.6 ug/l during mid-May through July to 13.7 ug/l by mid September. This translates to a 19.4 kg P epilimnetic/metalimnetic load increase from early August through mid-September. 19.4 kg P in the epilimnion/metalimnion plus 65 kg P internal load in the hypolimnion provided a total internal P load of 84.4 kg (table 3-1) on September 16, 2008. After mid-September, epilimnetic phosphorus loads continued to increase while hypolimnetic P decreased. This scenario supports the possibility of cyanobacteria movement upwards through the water column, which later formed surface scums that were observed the first week of October, 2008 after fall-turnover. Oxygen concentrations in the metalimnion and upper hypolimnion (6-8 meter depth) slightly increased after mid-September. This may have slightly decreased the rate of internal phosphorus loading at the water sediment interface for portions of the lake that are approximately 8 meters deep.

A Comparison of internal phosphorus loading and increased algal productivity as measured by reductions in water clarity

Water clarity greatly decreased in early August as secchi depth measurements were reduced from an April-July mean of 3.93 meters to an August-October mean of 2.50, a 35 percent clarity decline (figure 3-19). Diatoms were the dominant algal family from mid-August to late September. The cumulative internal P load increased from approximately 4 kg P in late-June to 32 kg P over a two to three week period in early-August. As a result, a 28 kg P load increase from late-June to early-August led to increased productivity and an immediate decline in water clarity by mid-August.

The Relationship between internal phosphorus loading to a dominance of Cyanobacteria

Cyanobacteria cell abundance became dominant in the epilimnion and metalimnion (7 meter plankton haul) in late July and the middle of August, when anoxia was well established, allowing internal phosphorus loads to be utilized by Cyanobacteria that migrate between epilimnetic and hypolimnetic waters (Sandgren, 1988). Cumulative internal P loading at this time was approximately 37 kg P above mid-June, in-lake phosphorus mass, prior to the start of summer internal P loading. Cumulative internal phosphorus loads were between 40 and 85 kg greater than mid-June levels, throughout the month of September. Cyanobacteria cells again dominated in early October, following fall-turnover.

Accounting for internal loading impact and in-lake phosphorus concentrations predicted by the loading model developed by Vollenweider (1976)

The following two figures provide phosphorus concentration predictions according to two scenarios; spring, fully-mixed in-lake conditions with no active internal phosphorus loading (figure 4-1) and late summer conditions with internal phosphorus loading (figure 4-2). Annual phosphorus loads estimated in the 1981 D-H study and 1990 DES Diagnostic Study were approximately 618 kg P for a normalized, (42 inch rainfall year), but assumed no internal loading. If 618 kg P is applied to the Vollenweider equation to predict in-lake P concentrations, the estimate would equate to13.5 ug/l P. This is similar to measured spring in-lake conditions from 2006 through 2008 which varied from 12 ug/l to 15 ug/l. If the cumulative internal phosphorus load estimate of 84.4 kg P (September 16, 2008) is included in the Vollenweider equation, the predicted in-lake P concentration equals 15.3 ug/l. This slightly underestimates the volume weighted fall in-lake concentration of 16.4 ug/l measured in early October, 2008.

Parameter	Units	Equation	Value (Study Period)
Lake area (A)	m^2	measured	2,477,500
Lake volume (V)	m^3	measured	13,011,788
Lake discharge (Q)	m^3	measured	25,513,310
Hydraulic Residence Time (T)	yr	T=V/Q	0.51
Mean depth (Z mean)	m	measured	5.50
Flushing rate	yr^{-1}	Flushing Rate = 1/T	1.96
Total Annual Loading (Pload)	kg	estimated to generate fully mixed P conc.	**618**
Internal P load	kg	estimated	**0**
Surface overflow rate (qs)	m	qs=Zmean/T	10.78
P coefficient (R)	N/A	R=0.426exp(-0.271qs)+0.574exp(-0.00949qs)	0.5411
Total areal P loading (L_p)	$g/m^2/yr$	L_p=P*1000/A	0.2494
Vollenweider in-lake P concentration	mg/L or g/m^3	$P = \frac{Lp}{qs}\left[\frac{1}{1+\sqrt{\frac{z}{qs}}}\right]$	**0.0135**

Figure 4-1: Vollenweider in-lake P concentration prediction with no internal P loading, yielding 13.5 ug/l.

Parameter	Units	Equation	Value (Study Period)
Lake area (A)	m^2	measured	2,477,500
Lake volume (V)	m^3	measured	13,011,788
Lake discharge (Q)	m^3	measured	25,513,310
Hydraulic Residence Time (T)	yr	T=V/Q	0.51
Mean depth (Z mean)	m	measured	5.50
Flushing rate	yr^{-1}	Flushing Rate = 1/T	2.0
Total Annual Loading (Pload)	kg	estimated based upon D-H Study	**618**
Internal P load through 9/16/08 (100% total internal P load, hypo and epi samples)	kg	estimated based upon internal phosphorus loading, 2008	**84**
Surface overflow rate (qs)	m	qs=Zmean/T	10.78
P coefficient (R)	N/A	R=0.426exp(-0.271qs)+0.574exp(-0.00949qs)	0.5411
Total areal P loading (L_p)	$g/m^2/yr$	L_p=P*1000/A	0.2835
Vollenweider in-lake P concentration	mg/L or g/m^3	$P = \frac{Lp}{qs}\left[\frac{1}{1+\sqrt{\frac{z}{qs}}}\right]$	**0.0153**

Figure 4-2: Vollenweider in-lake P concentration prediction with internal P loading, yielding 15.3 ug/l.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Webster Lake, Franklin, New Hampshire, 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. Additionally, Webster Lake has been listed for aquatic life use impairment in 2010, for not meeting phosphorus and chlorophyll-a criteria, since the 10 year median TP of 10 ug/L and Chl-a of 4.36 ug/l exceeds the criteria (8 ug/l TP and 3.3 mg/l Chl-a) for oligotrophic lakes.

The watershed plan developed by VHB (2006) based internal loading estimates on hypolimnetic concentrations ranging from 20 to30 ug/l (15 kg/yr). Data collected during the 2008 study measured July hypolimnetic phosphorus concentrations of 80 ug/l and 170 ug/l by mid-September resulting in an internal P loading estimate of 84.4 kg. Figure 5-1 demonstrates that this resulted in increased biological productivity measured by chlorophyll-a, initially dominated by the cyanobacteria *Anabaena* in late July and the middle of August, followed by the succession of the diatom *Tabellaria* in September and again by *Anabaena* in October, post fall turnover. The re-distribution of annual hypolimnetic phosphorus likely contributed to cyanobacteria scums measured in previous years.

Minimizing excessive cyanobacteria cell production and resultant cyanobacteria scums will likely require summer and fall, fully-mixed in-lake concentrations, not exceeding 12 ug/l. The Vollenweider equation estimates the permissible load to achieve this in-lake goal is approximately 540 kg per year. Since watershed P loads and internal P loads account for an estimated 618 kg and 84 kg P, respectively, 151 kg P would be the target for watershed and in-lake source removal to achieve an in-lake P concentration goal of 12 ug/l. This compares well with the recommendation outlined in the Webster Lake Watershed Management Plan (VHB, 2006) which determined that an annual P load reduction of 140 kg would be needed to reduce the in-lake P concentration by 3 ppb, from 15 ug/l to 12 ug/l. Reductions in any P loads should result in varying water quality improvements, including increased clarity and reduced incidences and magnitudes of cyanobacteria blooms and scums. The more phosphorus removed, the greater lake improvements can be expected.

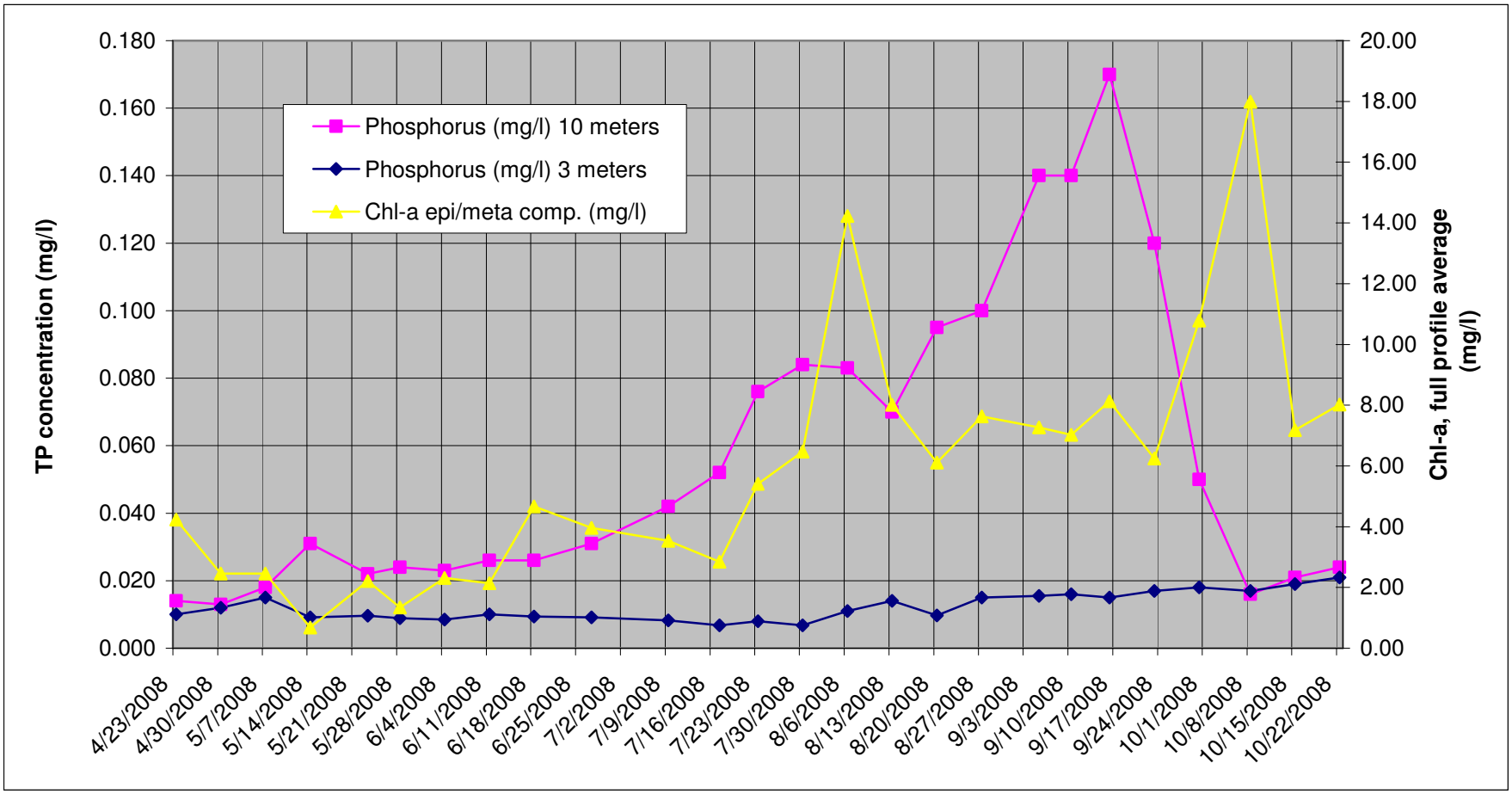


Figure 5-1: Epilimnetic (3 m) and Hypolimnetic (10 m) phosphorus concentrations with Chl-a epi/meta composite concentrations, April-October, 2008.

Note: Chl-a data not collected on 4/30/08 and 5/7/08. Therefore, data points in this figure represent average Chl-a values from 4/23/08 and 5/14/08 values.

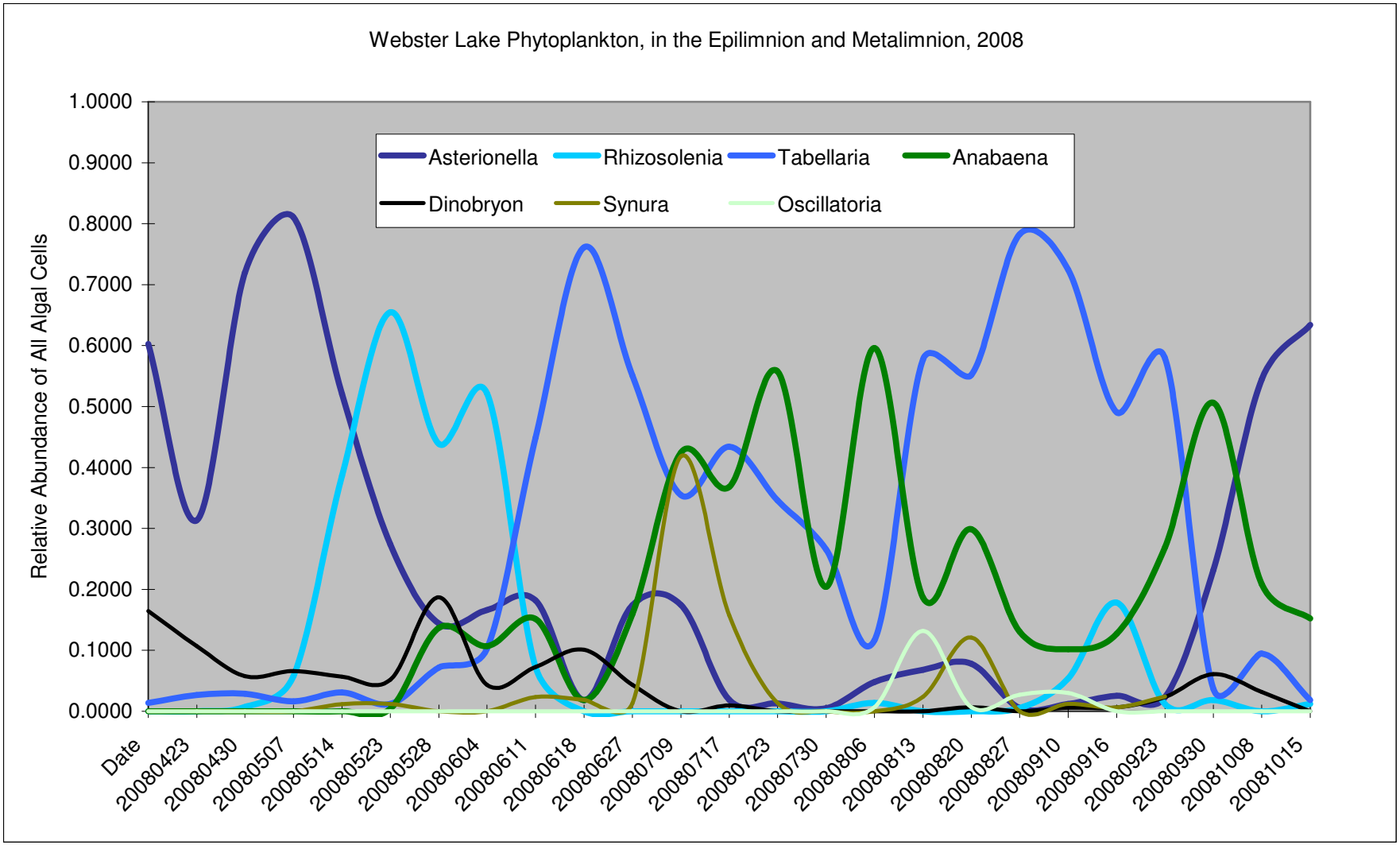


Figure 5-2: Webster Lake Phytoplankton and Cyanobacteria Succession, Relative Abundance, 2008

5.1 Watershed Management

As provided in the Webster/ Highland Lake Watershed Management Plan (VHB, 2006) it is essential that best management practices for near shore and near tributary lots 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 pond or to areas where infiltration is possible. In addition, increasing lake and tributary setbacks for septic systems and implementing stormwater best management practices for all developed land in the watershed will have a significant benefit in maintaining lake water quality over the long term. Equally important is the maintenance of forest cover in the rest of the watershed. As shown in Section 4.0 of this report, by early-August, internal loads of only 33 kg P resulted in increased Chl-a and reduced water clarities. Therefore, even small P load reductions, totaling only 30-40 kg P, will likely result in significant water quality improvements assuming all other watershed loads do not increase.

5.2 In-lake Treatment- Phosphorus Inactivation

There are in-lake restorative techniques that provide positive results in reducing internal sediment P loading to 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, Cooke et al, 1986). Each technique was evaluated to effectiveness in improving lake quality over a known time period and the methodology cost/benefit ratios. These in-lake techniques include aeration, circulation, biomanipulation, dredging, water exchange and a series of chemical inactivation processes. One proven technique considered for sediment phosphorus loading is phosphorus inactivation with aluminum salts. The technique and its use in New Hampshire lakes are described below.

Phosphorus precipitation and sediment P inactivation through aluminum salts injection are lake restoration techniques that reduce phosphorus in the water column 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 to the lake. (Cooke et al, 1977; Larson, 1979). It is important to stress that all watershed P sources be reduced or eliminated prior to the use of this technique. Watershed P inputs would counteract any in-lake restorative techniques and lead to a waste of any in-lake project money and minimal lake quality improvements. The key to such in-lake phosphorus reduction products is the simultaneous reduction of watershed phosphorus loading to the lake.

Benefits of aluminum salts injection include the reduction of in-lake phosphorus concentration and internal sediment loading, increased transparency, reductions in algal

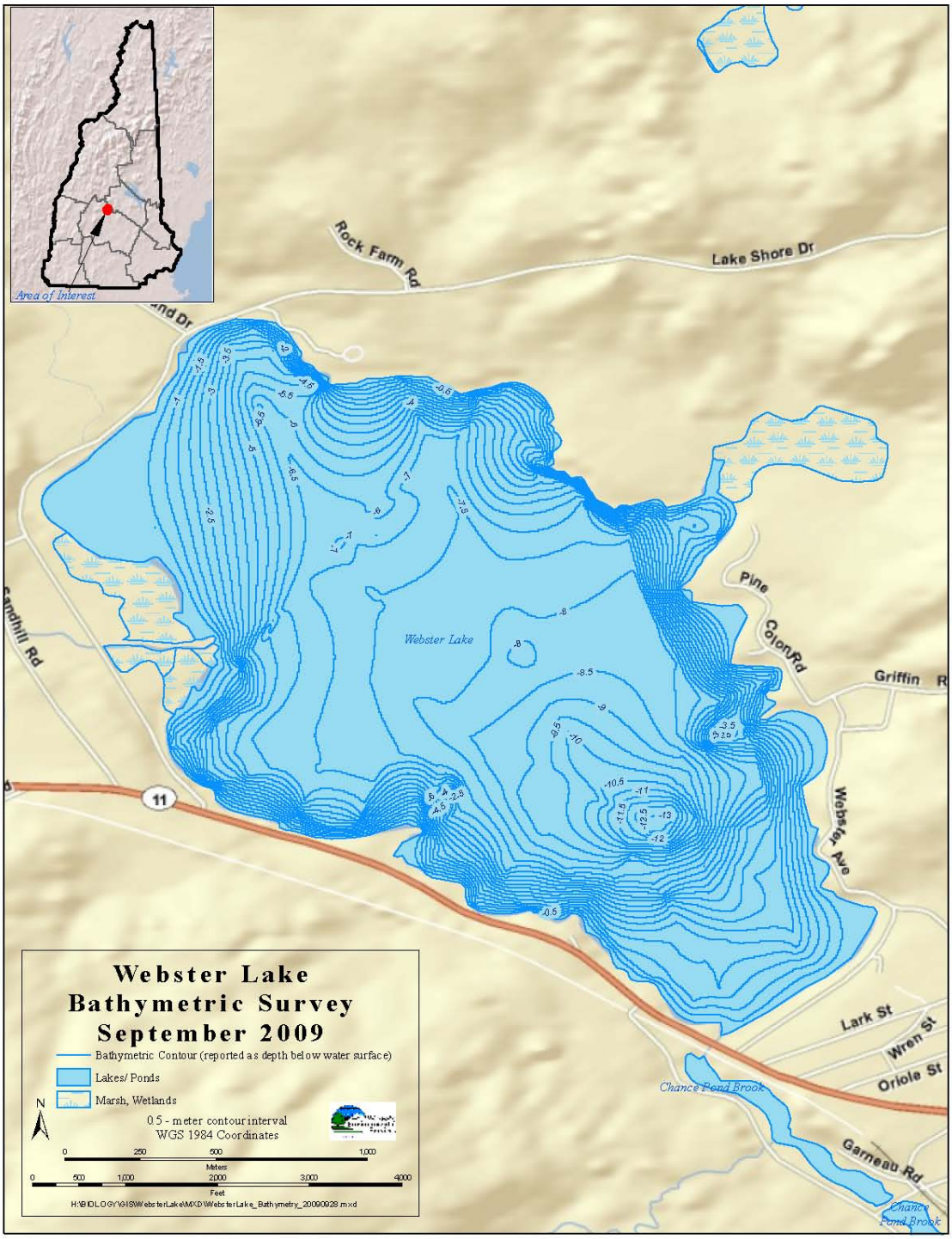
or cyanobacteria abundance and cell dominance shifts from cyanobacteria to other algal populations.

Potential drawbacks of this procedure deal with the chemical reactions in the water from the added compounds. Lakes with low buffering capacity (low ANC), small doses of aluminum sulfate can exhaust the buffering capacity to a point that causes lake pH to fall below 6.0. When this happens, aluminum may be released from the compound, causing aluminum toxicity to occur. There are methods to ameliorate this potential, which involve adding salts to buffer the acidity. The increase of aquatic plant growth due to an increase of light transmission is sometimes considered a drawback. As lake clarity increases, sunlight penetration extends to greater depths. This allows for 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 important invertebrate populations.

A local example of hypolimnetic aluminum salt treatment is 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 aluminates were used as sediment phosphorus inactivants to improve lake quality (Connor, 1986). The treatment occurred during June of 1984. A four-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). An immediate impact of treatment was a reduction in the depletion of oxygen in the hypolimnion, resulting in the maintenance of oxygen in the hypolimnion, a decrease in algal and cyanobacteria abundance (measured by chlorophyll-a concentration and microscopic cell counts), improved transparency, a shift from cyanobacteria dominance to species of algae typical to New Hampshire lakes and ponds and an increase of 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). Now, more than twenty-five years later, the lake is still showing signs of good water quality.

If Aluminum salts treatment for Webster Lake were necessary, it would cost more than $100,000. Furthermore, some treatments are met with limited success, especially if watershed BMPs has not been implemented. Therefore, in-lake treatments would only be a consideration following implementation of BMPs in the Webster/ Highland Lake Watershed Management Plan (VHB, 2006) and reduction of watershed phosphorus sources to pre-development or low-level impact conditions.

Appendix A


Webster Lake
Bathymetric Survey
September 2009
Bathymetric Contour (reported as depth below water surface)
Lakes/ Ponds
Marsh, Wetlands
0.5 - meter contour interval
WGS 1984 Coordinates
Meters
Feet
Area of Interest
Rock Farm Rd
Lake Shore Dr
Webster Lake
Pine Colony Rd
Griffin R
Webster Ave
Lark St
Wren St
Oriole St
Garneau Rd
Chance Pond Brook
Sandhill Rd
11

Bibliography

Connor, J.N. and G.N. Smith. 1983. Kezar Lake Diagnostic/Feasibility Study. Final Report. New Hampshire Water Supply and Pollution Control Commission. Staff Report No. 35. 690 pp.

Connor, J.N. and G.N. Smith. 1986. An Efficient Method of Applying Aluminum Salts for Sediment Phosphorus Inactivation of Lakes. American Water Resources Bulletin. 22:661-664

Connor, J.N. and A.P. Smagula. 2000. A Study of the Effectiveness, Longevity, and Ecological Impacts of Hypolimnetic Aluminum Injection in Kezar Lake, North Sutton, New Hampshire. Final Report. New Hampshire Dept. of Env. Svcs. NHDES-WD-00-2.

Connor, J.N. and M.R. Martin. 1989. An Assessment of Sediment Phosphorus Inactivation, Kezar Lake, New Hampshire. Water Resources Bull. 25(4):845-853.

Cooke, G.D., M.R. McComas, D.W. Waller and R.H. Kennedy. 1977. The Occurrence of Internal Phosphorus Loading in Two Small, Eutrophic, Glacial Lakes in Northeastern Ohio. Hydrogeol. 56:129-135

Cooke, G.D., E.B. Welch, S.A. Perterson and P.R. Newroth. 1986. Lake and Reservoir Restoration. Butterworths Pub. 392 pp.

Cooke, G.D., E.B. Welch, S.A. Peterson and P.R. Newroth, 1993. Restoration and Management of Lakes and Reservoirs. 2nd Edition. Lewis Publishers. 548 pp.

Smith, V.H. 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. Science, 221 669-71.

Trowbridge, P., 2008. Nutrient Criteria by Trophic Class Discussion Paper.

Trowbridge, P., 2009, Assessment of Chlorophyll-*a* and Phosphorus in New Hampshire Lakes for Nutrient Criteria Development. (R-WD-09-29)

Vannesse Hangen Brustlin, 2006. Webster/Highland Lakes Watershed Management Plan. Franklin/Andover, New Hampshire.

Vollenweider, R.A. 1975. Input-output Models, with Special Reference to the Phosphorus Loading Concept in Limnology. Schweiz. Z. Hydrologic. 37:53-84.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication Mem. Ist. Ital. Idrobiol. 33:53-83.