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March 26, 2014

Mr. Cory Mathisen
Minnesota Pollution Control Agency
Municipal Waste Water Section
520 Lafayette Road North
St. Paul, MN 55455-4194

Re: Submittal of Annual Report and Discussion of Observed Results from the Crystal Lake Water Treatment Facility, City of Robbinsdale, MN

Dear Mr. Mathisen,

It is the purpose of this letter to provide the monitoring results for the City of Robbinsdale's Crystal Lake Surface Water Treatment Facility for the 2013 operational period.

Outlined below are the observed results from the 2013 operational period. Attached are tables, graphs, and figures as required the Annual Reporting requirements, identified in Chapter 1, Section 1, 1.2 on page 9 of the permit for the project.

1. Facility's ability to remove phosphorus and other pollutants.

Background

The Crystal Lake Flocculation Treatment System began operation and treatment of surface water on May 6, 2013 and has been operated through October 20, 2013.

Operation of the treatment facility was performed within the parameters of the permits requirements, which included sampling and analysis of the influent and effluent water and measurement of the volume of water treated. I note that the Discharge Monitoring Reports were submitted online monthly and the data provided within this submittal reflect slightly more than what is required in the annual reporting requirements for the project.

Influent and Effluent Sampling and Analysis

Influent and effluent sampling was performed at the inlet and outlet of the facility (refer to attached Figure 1 for their specific locations). Sampling occurred on a weekly basis for the key organic pollutants and on a monthly or quarterly basis for inorganic pollutants or basic metals, in accordance with permit requirements. Refer to the attached tables, graphs, and figure for further information.

Sampling of the influent and effluent water from the facility occurred at several locations, as shown in the attached figure. When the Facility draws water from the epilimnion level of the lake, the influent sampling occurred from the lake shore, one foot below the water surface, adjacent to the inlet. When the facility draws water from the hypolimnion level of the lake, water was sampled from within the lift station, at the inlet pipe. Note, when sampling from within the lift station the reagent pump was shut off and the lift station pump continued to operate for a minimum of 20 minutes before sampling occurred to ensure that no residual reagent affected the sample results. Effluent sampling occurred from within the clarifier, one foot below the water surface, adjacent to the outlet. Samples were collected with a standard dipper that was routinely rinsed several times prior to sample collection. Samples were placed in sample bottles provided by the selected laboratory, placed on ice, and delivered to the laboratory within 24 hours of collection.

2. Facility performance and the ability to remove phosphorus and other pollutants.

Outlined below is a summary of the pollutant reductions observed during facility operation, refer to the attached Tables and graphs for complete results:

Total Phosphorus Monitoring Results:

- Average Total Phosphorus Influent Concentration: 0.27 (mg/L)
- Average Total Phosphorus Effluent Concentration: 0.03 (mg/L)
- Total Phosphorus Reduction Percentage: 88%
- Total Phosphorus Pounds Removed: 208 (lbs)

Ortho Phosphorus Monitoring Results:

- Average Ortho Phosphorus Influent Concentration: 0.12 (mg/L)
- Average Ortho Phosphorus Effluent Concentration: 0.01 (mg/L)
- Ortho Phosphorus Reduction Percentage: 92%
- Ortho Phosphorus Pounds Removed: 93 (lbs)

Please note that the Ortho Phosphorus monitoring results were routinely at or below laboratory detection limits.

Total Suspended Solids Monitoring Results:

- Average Total Suspended Solids Influent Concentration: 16 (mg/L)
- Average Total Suspended Solids Effluent Concentration: 11 (mg/L)
- Total Suspended Solids Reduction Percentage: 69%
- Total Suspended Solids Pounds Removed: 4,787 (lbs)

pH Level Monitoring Results:

- Average pH Influent Concentration: 8.07
- Average pH Effluent Concentration: 7.04
- Change in pH Percentage: 13%

Findings

As part of the operation and continued optimization of the influent and effluent treatment process for the Facility, the following has been examined:

a. How much phosphorus was removed from the Lake?

- Based on the second year monitoring results, 208 pounds of phosphorus was removed from the lake. During the design process, an annual removal of 80 to 120 pounds removed was initially estimated. By being able to pump water from the hypolimnion level of the lake for extended period of time, the facility was able to increase the removals by almost 60% due to the higher concentrations of Phosphorus. It is still anticipated that in coming years the annual Phosphorus load reductions will be increased.

b. How did the Facility perform in removing other pollutants?

- Ortho phosphorus within the Lake was reduced by 93 pounds.
  - Typical effluent ortho phosphorus results were consistently below detection limits and often were at a non-detect level.

- Total Suspended Solids within the Lake was reduced by over 4,780 pounds.
  - Removal of total suspended solids was lower in 2013 than in 2012 due to the extended period drawing water from the hypolimnion level of the lake and the limited amount of suspended solids in this portion of the lake.

- Dissolved Aluminum results were consistent in the first portion of the treatment season. However, later in the season the concentration increased considerably. It is believed that this spike in dissolved aluminum is caused by overdosing the reagent due to elevated levels of algae, which seems to absorb the reagent and reduces the overall treatment effectiveness.
  - Additional measures to reduce the dissolved aluminum spikes are being considered, such as limiting the amount of reagent being titrated, further anticipation of weather trends and how temperature affects reagent reaction, and continued measurement of the water clarity to ensure the suspended floc stays several feet below the water surface by making fine adjustment to the reagent dosage.

- pH levels stayed fairly consistent throughout the operation period due to the slightly alkaline levels of the influent lake water and were able to remain within range with the treatment process.
  - pH reductions were slight enough that the sodium hydroxide buffer solution was not used during the 2013 operation period but was on hand if pH levels were to drop below 6.0.

c. How well did the facility operate during the second year of operation and were any modifications made to the facility?

- The treatment facility operated as planned and no significant operational issues occurred during the 2013 operational monitoring period.

- Routine maintenance activities did occur during the monitoring period, such as replacement of the metering peristaltic tubes, reattachment of the skimmer discharge pipe, and general housekeeping activities.

d. How much reagent is required to effectively operate the facility?

Aluminum Sulfate

- In the spring and early summer, when phosphorus levels are typically low in the epilimnion level of the lake, the facility draws water from the hypolimnion level of the lake where phosphorus concentrations are typically between 0.4 mg/L to 0.7mg/L.
  - In this condition, the typical the reagent dosage rates for treatment of the hypolimnion water ranges from 0.08 ml/L to 0.12 ml/L, it is anticipated that this dosage rate will provide about a 90 percent phosphorus reduction.

- In late summer, the Facility would switch to the epilimnion layer of the lake when phosphorus levels were observed to be between 0.06 ml/L to 0.08 ml/L.
  - In this condition, the typical the reagent dosage rates for treatment of the epilimnion water ranges from 0.1 mg/L to 0.25 mg/L, it is anticipated that this dosage rate will provide about a 90 percent phosphorus reduction.

- Actual dosage rates require field verification of in-lake conditions, ambient temperature, and pumping rates to determine the most precise and cost effective rates.

Sodium Hydroxide

- Sodium hydroxide was not used during the 2013 due to the refinement of the treatment process. Sodium Hydroxide was readily available if the pH levels had dropped below 6.0.

3. Measurement of treated water volume:

Background

Lift station pumping rates were measured to determine the volume of water treated by the facility and to accurately measure pollutant reductions, and reagent dosage rates.

Treated water volume was monitored by measuring the depth of water over a 4, 6, and 8-inch orifice at the outlet of the clarifier.

Results

- Water volume treated by the facility is estimated at 321 acre-feet, or about 25% of the lake volume.
- It is estimated the facility reduced the phosphorus loading from over one third of the 1,237 acre watershed.
- Refer to Table 14 and Figures 1 in Section 4.III of this report for further information.

Findings:
As part of the optimization of the flow measurement process for the treatment facility, the following was examined:

a. **What is the maximum volume of water the facility can pump?**
   - o Maximum pumping rate was measured at 574 gph with both pumps at 57 MHz.
   - ▪ Pumping rates can vary considerably due to fluctuating lake levels and are routinely monitored.

b. **What is the optimum pumping rate?**
   - o Throughout the 2013 operational period the primary pumping rate is 440 gph, which is typically a single pump running at 60 MHz, based on pollutant reductions observed in the monitoring results.

   - o Towards the end of the 2013 operational season, both lift station pumps were experimented with by slowly raising the MHz of each pump slowly, the most effective pumping rate was up to 57 MHz or 574 gpm.

   - ▪ Increased lift station pumping rates have been found to only be effective when the Facility draws from the hypolimnion level of the Lake where there is more phosphorus available to be removed.

   - ▪ Pumping rates can vary considerably due to fluctuating lake levels and are routinely monitored.

4. **Recommendations for facility operation in 2014:**

a. **Schedule**
Based on the monitoring results for the 2013 monitoring period, the facility will become operational as weather conditions allow, typically late April or early May, and will operate into late October.

b. Anticipated operational parameters and reagent dosage rates

- Influent water will be drawn from the hypolimnion level of the Lake until mid-summer.

  - Anticipated dosage rates for this period will vary from 0.06 to 0.12 ml/L to treat phosphorus levels that typically range from 0.4 to 0.7 mg/L.

  - Anticipated phosphorus reductions will range from 88 to 90 percent with total reduction of 1.5 to 3.0 pounds per day.

- Influent water will be drawn from the epilimnion level of the Lake from mid-summer into early fall.

  - Anticipated dosage rates for this period will vary from 0.1 to 0.25 ml/L to treat phosphorus levels that typically range from 0.05 to 0.1 mg/L.

  - Anticipated phosphorus reductions will range from 85 to 88 percent with total reduction of 0.17 to 0.25 pounds per day.

  - Limited phosphorus reductions when the facility is drawing water from the epilimnion level are due to the limited amount of available phosphorus and the amount of reagent required to remove algae. However, the facility can reduce phosphorus levels within the Lake from 0.06 mg/L to 0.015 or to detection limits cost effectively.

5. Sampling and Analysis:

a. Sampling for Organic Pollutants and Metals Schedule

Sampling for primary organic pollutants and metals, identified below, will occur on a weekly and monthly basis in 2014. This analysis will provide the data necessary to determine that the facility is operating efficiently and to determine the load reductions during operation.

- Total Phosphorus
- Ortho Phosphorus
- Total Suspended Solids
- Dissolved Aluminum
- Total Aluminum

b. Sampling for Inorganic Pollutants and Metals Schedule

Based on 2012 and 2013 monitoring data for inorganics and metals, outlined below, there was little to no change in these parameters.

- Dissolved Potassium
- Total Potassium
- Dissolved Sulfate
- Total Sulfate
- Total Sodium Cations
- Total Sodium
- Total Calcium
- Total Magnesium

- Based on 2012 and 2013 monitoring data, we believe that the influent and effluent results for these inorganic and metal parameters has reflected little to no change we believe provides little value to the overall treatment process and are no longer necessary to perform the required monitoring.
- As outlined in Chapter 2, Line 2 of the permit for this project, we formally request the reduction in monitoring requirements to be in line with the Small Municipal Separate Storm Sewer System (MS4) permit requirements. In addition, it is costly to provide sample and analysis for these parameters.

We thank you for working with us on the Crystal Lake Flocculation Treatment Facility and we look forward to continue working with you into the future.

If you would like to further discuss the facility's performance, results, or sampling and analysis reductions please feel free to contact me by phone or email at ☎ 763-531-1260 or at rmccoy@ci.robbinsdale.mn.us .

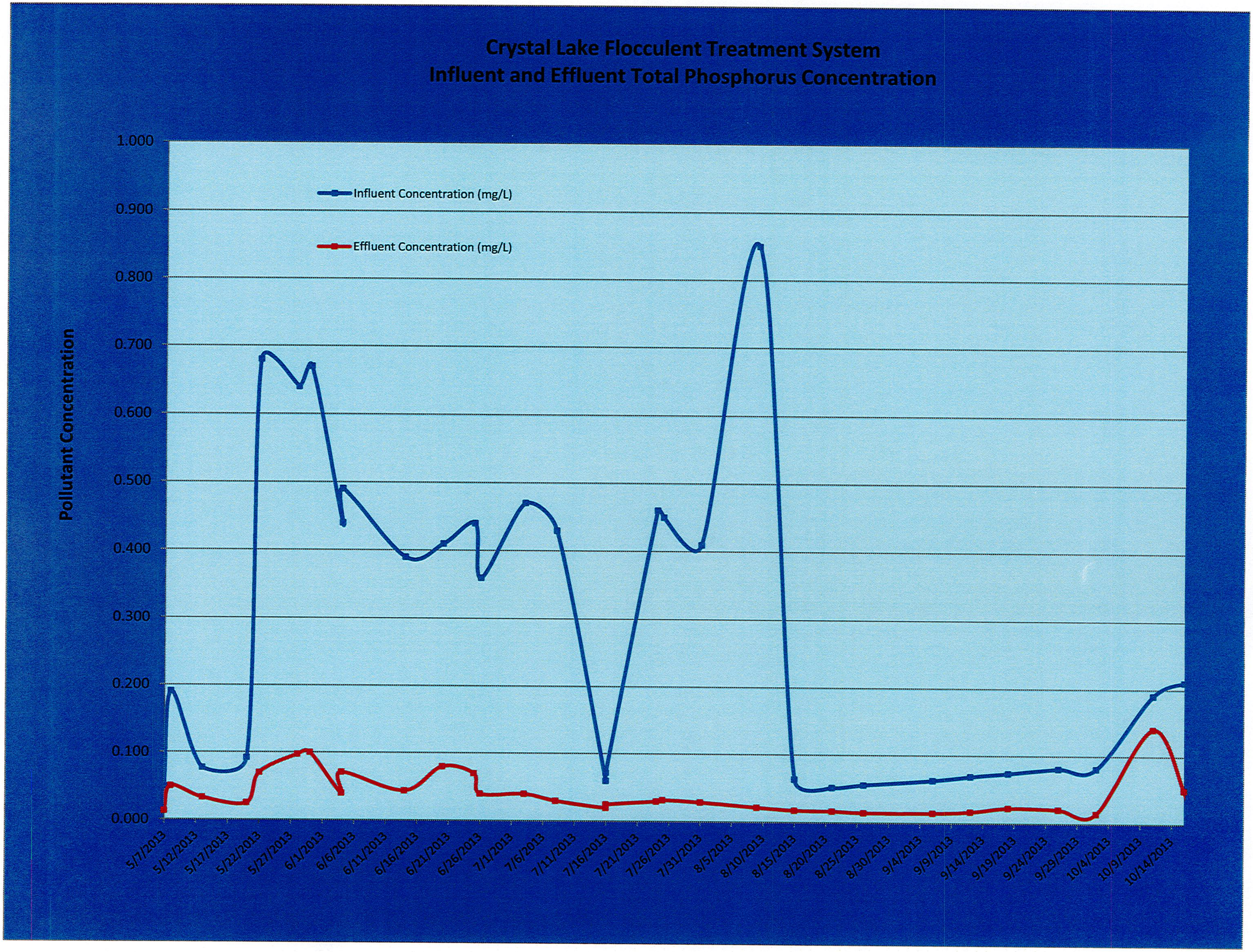
Yours sincerely

Richard McCoy, P.E.
Public Works Director / City Engineer

Surface Water Treatment Results

Total Phosphorus					
Sampling Date	Influent Concentration (mg/L)		Effluent Concentration (mg/L)	Reduction (mg/L)	Percent Reduction
5/7/2013	0.049		0.013	0.04	73%
5/8/2013	0.190	tc	0.050	0.14	74%
5/13/2013	0.077		0.033	0.04	57%
5/20/2013	0.092		0.025	0.07	73%
5/22/2013	0.680	tc	0.070	0.61	90%
5/28/2013	0.640		0.097	0.54	85%
5/30/2013	0.670	tc	0.100	0.57	85%
6/4/2013	0.440	tc	0.040	0.40	91%
6/4/2013	0.490		0.071	0.42	86%
6/14/2013	0.390		0.044	0.35	89%
6/20/2013	0.410		0.080	0.33	80%
6/25/2013	0.440		0.070	0.37	84%
6/26/2013	0.360		0.040	0.32	89%
7/3/2013	0.470		0.040	0.43	91%
7/8/2013	0.430	tc	0.030	0.40	93%
7/16/2013	0.060	tc	0.020	0.04	67%
7/16/2013	0.072		0.025	0.05	65%
7/24/2013	0.460	tc	0.030	0.43	93%
7/25/2013	0.450		0.032	0.42	93%
7/31/2013	0.410		0.029	0.38	93%
8/9/2013	0.850		0.022	0.83	97%
8/15/2013	0.064		0.018	0.05	72%
8/21/2013	0.052		0.017	0.04	67%
8/26/2013	0.056		0.015	0.04	73%
9/6/2013	0.063		0.015	0.05	76%
9/12/2013	0.069		0.017	0.05	75%
9/18/2013	0.074		0.023	0.05	69%
9/26/2013	0.081		0.021	0.06	74%
10/2/2013	0.081		0.015	0.07	81%
10/11/2013	0.190		0.140	0.05	26%
10/16/2013	0.210		0.050	0.16	76%
10/17/2013	0.200		0.016	0.18	92%

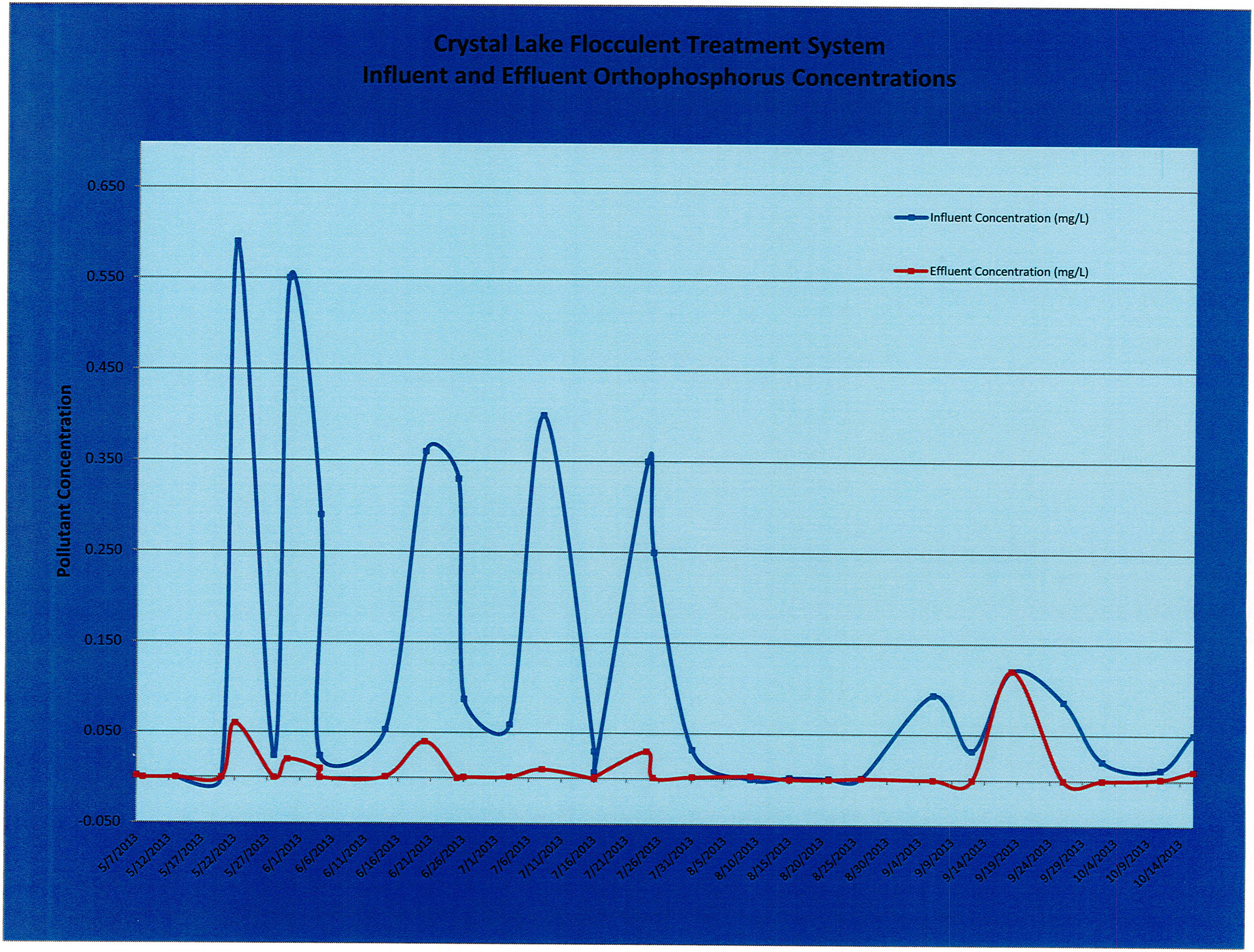
J: Detected but below the Method Reporting Limit and is considered as ND
ND: Not Detected
BR: Sample analysis performed by Braun Intertec
TC: Sample analysis by William Lloyd Tri-City Laboratory
AH: Denotes Aqua Hawk reagent used


Crystal Lake Flocculent Treatment System
Influent and Effluent Total Phosphorus Concentration
Influent Concentration (mg/L)
Effluent Concentration (mg/L)
Pollutant Concentration
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
5/7/2013
5/12/2013
5/17/2013
5/22/2013
5/27/2013
6/1/2013
6/6/2013
6/11/2013
6/16/2013
6/21/2013
6/26/2013
7/1/2013
7/6/2013
7/11/2013
7/16/2013
7/21/2013
7/26/2013
7/31/2013
8/5/2013
8/10/2013
8/15/2013
8/20/2013
8/25/2013
8/30/2013
9/4/2013
9/9/2013
9/14/2013
9/19/2013
9/24/2013
9/29/2013
10/4/2013
10/9/2013
10/14/2013

Surface Water Treatment Results

Ortho Phosphorus						
Sampling Date	Influent Concentration (mg/L)		Effluent Concentration (mg/L)		Reduction (mg/L)	Percent Reduction
5/7/2013	0.002	j	0.002	j	0.0005	23%
5/8/2013	0.000	ND	0.000	ND	0.0000	100%
5/13/2013	0.000	ND	0.000	ND	0.0000	100%
5/20/2013	0.000	ND	0.000	ND	0.0000	100%
5/22/2013	0.590		0.060		0.5300	90%
5/28/2013	0.024		0.000	j	0.0240	100%
5/30/2013	0.550		0.020		0.5300	96%
6/4/2013	0.290		0.010		0.2800	97%
6/4/2013	0.024		0.000	ND	0.0240	100%
6/14/2013	0.053		0.001	j	0.0518	98%
6/20/2013	0.360		0.040		0.3200	89%
6/25/2013	0.330		0.000	ND	0.3300	100%
6/26/2013	0.087		0.001	j	0.0860	99%
7/3/2013	0.059		0.002	j	0.0575	97%
7/8/2013	0.400		0.010	j	0.3900	98%
7/16/2013	0.030		0.000	ND	0.0300	100%
7/16/2013	0.007		0.002		0.0054	78%
7/24/2013	0.350		0.030		0.3200	91%
7/25/2013	0.250		0.001	j	0.2488	100%
7/31/2013	0.032		0.002	j	0.0299	93%
8/9/2013	0.000	ND	0.003	j	-0.0033	-3300%
8/15/2013	0.002	j	0.000	ND	0.0018	100%
8/21/2013	0.001	j	0.000	ND	0.0010	100%
8/26/2013	0.002	j	0.001	j	0.0004	24%
9/6/2013	0.093	j	0.000	ND	0.0930	100%
9/12/2013	0.032	j	0.000	ND	0.0320	100%
9/18/2013	0.120	j	0.120	j	0.0000	0%
9/26/2013	0.086	j	0.000	ND	0.0860	100%
10/2/2013	0.021	j	0.000	ND	0.0210	100%
10/11/2013	0.012	j	0.002	j	0.0102	85%
10/16/2013	0.050	j	0.010	j	0.0400	80%
10/17/2013	0.014		0.001	j	0.0130	93%

J: Detected but below the Method Reporting Limit
ND: Not Detected

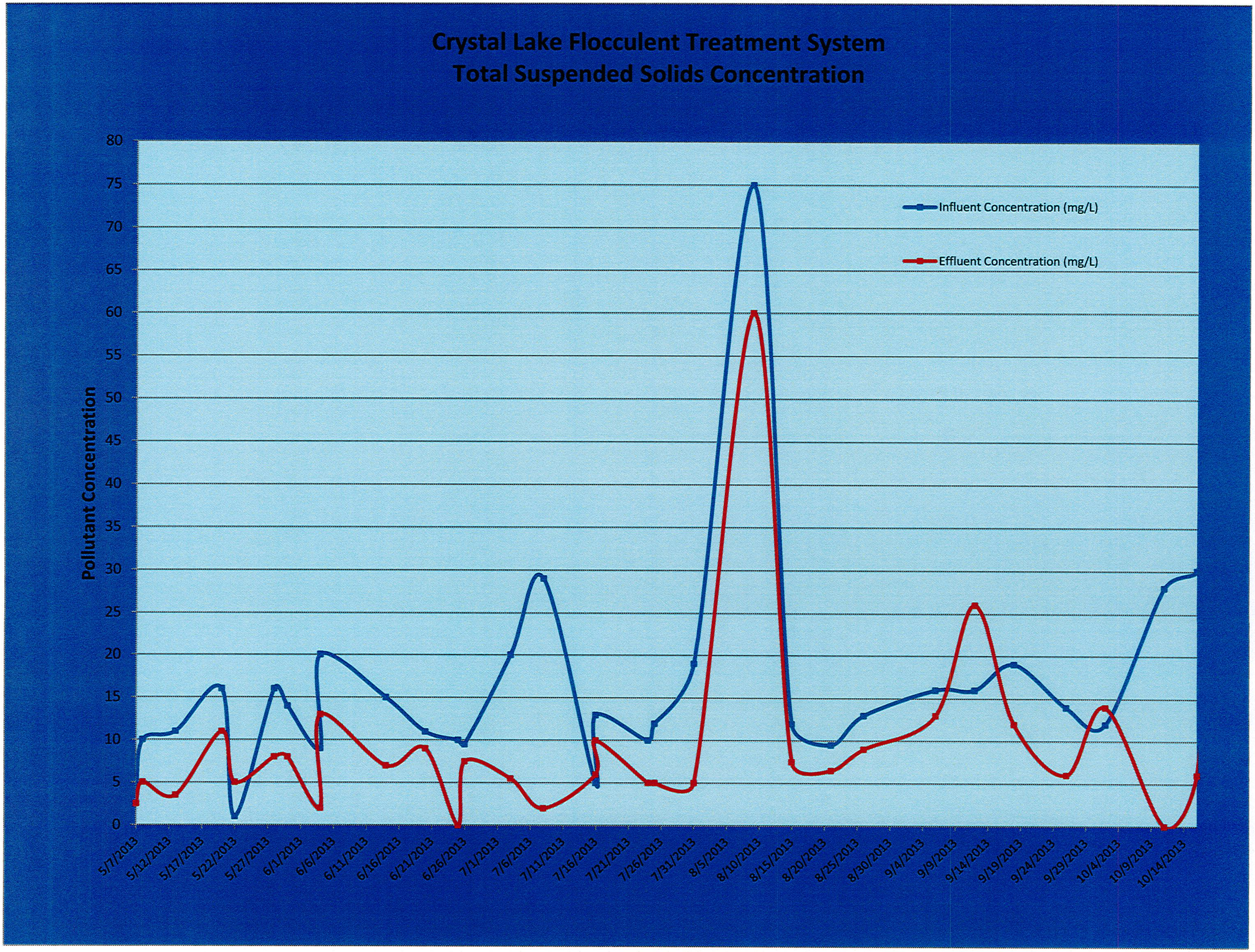


Crystal Lake Flocculent Treatment System
Influent and Effluent Orthophosphorus Concentrations
Pollutant Concentration
0.650
0.550
0.450
0.350
0.250
0.150
0.050
-0.050
Influent Concentration (mg/L)
Effluent Concentration (mg/L)
5/7/2013
5/12/2013
5/17/2013
5/22/2013
5/27/2013
6/1/2013
6/6/2013
6/11/2013
6/16/2013
6/21/2013
6/26/2013
7/1/2013
7/6/2013
7/11/2013
7/16/2013
7/21/2013
7/26/2013
7/31/2013
8/5/2013
8/10/2013
8/15/2013
8/20/2013
8/25/2013
8/30/2013
9/4/2013
9/9/2013
9/14/2013
9/19/2013
9/24/2013
9/29/2013
10/4/2013
10/9/2013
10/14/2013

Surface Water Treatment Results

Total Suspended Solids						
Sampling Date	Influent Concentration (mg/L)		Effluent Concentration (mg/L)		Reduction (mg/L)	Percent Reduction
5/7/2013	4	j	3	j	1.50	38%
5/8/2013	10		5		5.00	50%
5/13/2013	11		4	j	7.50	68%
5/20/2013	16		11		5.00	31%
5/22/2013	1		5		-4.00	-400%
5/28/2013	16		8		8.00	50%
5/30/2013	14		8		6.00	43%
6/4/2013	9		2		7.00	78%
6/4/2013	20		13		7.00	35%
6/14/2013	15		7		8.00	53%
6/20/2013	11		9		2.00	18%
6/25/2013	10		0	ND	10.00	100%
6/26/2013	9.5		7.5		2.00	21%
7/3/2013	20		5.5		14.50	73%
7/8/2013	29		2		27.00	93%
7/16/2013	5		6		-1.00	-20%
7/16/2013	13		10		3.00	23%
7/24/2013	10		5		5.00	50%
7/25/2013	12		5		7.00	58%
7/31/2013	19		5		14.00	74%
8/9/2013	75		60		15.00	20%
8/15/2013	12		7.5		4.50	38%
8/21/2013	9.5		6.5		3.00	32%
8/26/2013	13		9		4.00	31%
9/6/2013	16		13		3.00	19%
9/12/2013	16		26		-10.00	-63%
9/18/2013	19		12		7.00	37%
9/26/2013	14		6		8.00	57%
10/2/2013	12		14		-2.00	-17%
10/11/2013	28		0		28.00	100%
10/16/2013	30		6		24.00	80%
10/17/2013	36		27		9.00	25%

J: Detected but below the Method Reporting Limit
ND: Not Detected

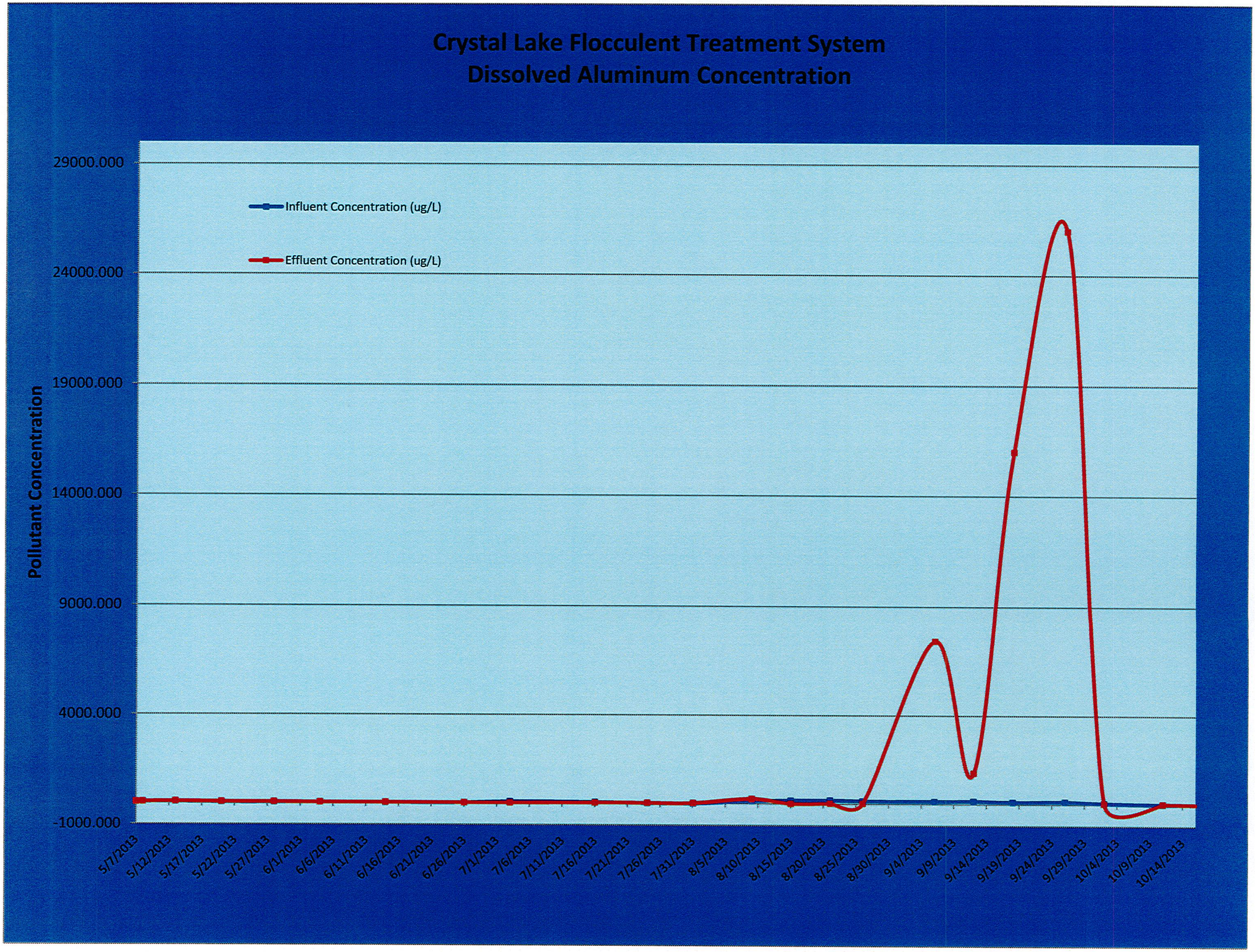


Crystal Lake Flocculent Treatment System
Total Suspended Solids Concentration
Pollutant Concentration
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Influent Concentration (mg/L)
Effluent Concentration (mg/L)
5/7/2013
5/12/2013
5/17/2013
5/22/2013
5/27/2013
6/1/2013
6/6/2013
6/11/2013
6/16/2013
6/21/2013
6/26/2013
7/1/2013
7/6/2013
7/11/2013
7/16/2013
7/21/2013
7/26/2013
7/31/2013
8/5/2013
8/10/2013
8/15/2013
8/20/2013
8/25/2013
8/30/2013
9/4/2013
9/9/2013
9/14/2013
9/19/2013
9/24/2013
9/29/2013
10/4/2013
10/9/2013
10/14/2013

Surface Water Treatment Results

Dissolved Aluminum						
Sampling Date	Influent Concentration (ug/L)		Effluent Concentration (ug/L)		Reduction (ug/L)	Percent Reduction
5/7/2013	17.000	j	15.000	j	2.00	12%
5/8/2013	23.000	j	21.000	j	2.00	9%
5/13/2013	29.000	j	42.000		-13.00	-45%
5/20/2013	9.500	j	19.000	j	-9.50	-100%
5/28/2013	9.500	j	19.000	j	-9.50	-100%
6/4/2013	12.000	j	9.500	j	2.50	21%
6/14/2013	7.300	j	9.200	j	-1.90	-26%
6/26/2013	7.200	j	6.500	j	0.70	10%
7/3/2013	58.000		8.500		49.50	85%
7/16/2013	43.000		24.000	j	19.00	44%
7/24/2013	11.000	j	20.000	j	-9.00	-82%
7/31/2013	6.700	j	18.000		-11.30	-169%
8/9/2013	120.000		220.000		-100.00	-83%
8/15/2013	150.000		7.600	j	142.40	95%
8/21/2013	160.000		21.000		139.00	87%
8/26/2013	130.000		18.000	j	112.00	86%
9/6/2013	120.000		7400.000		-7280.00	-6067%
9/12/2013	140.000		1400.000		-1260.00	-900%
9/18/2013	100.000		16000.000		-15900.00	-15900%
9/26/2013	120.000		26000.000		-25880.00	-21567%
10/2/2013	56.000		42.000		14.00	25%
10/11/2013	16.000	j	22.000	j	-6.00	-38%
10/17/2013	0.014		0.001	j	0.01	93%

J: Detected but below the Method Reporting Limit
ND: Not Detected

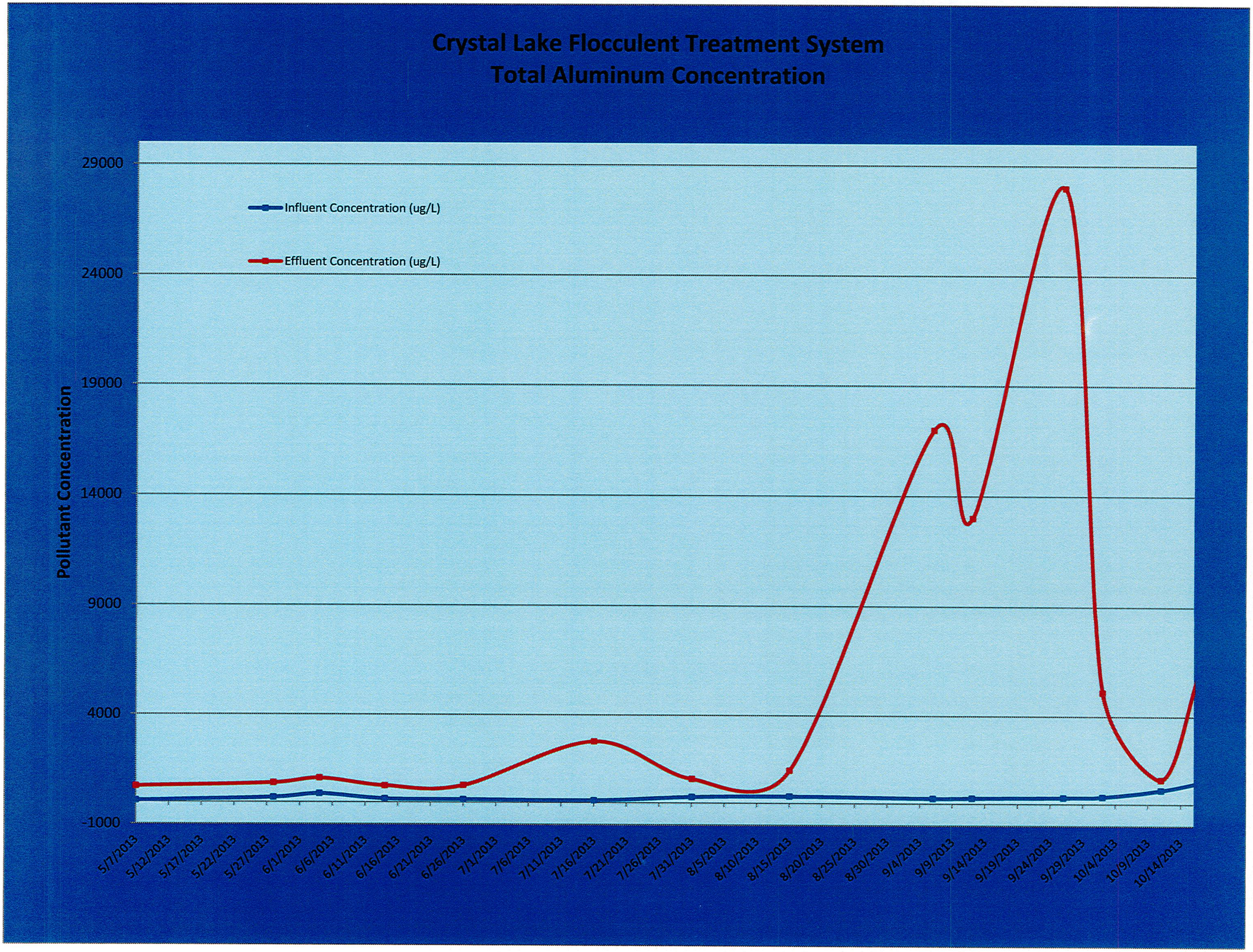


Crystal Lake Flocculent Treatment System
Dissolved Aluminum Concentration
Pollutant Concentration
29000.000
24000.000
19000.000
14000.000
9000.000
4000.000
-1000.000
Influent Concentration (ug/L)
Effluent Concentration (ug/L)
5/7/2013
5/12/2013
5/17/2013
5/22/2013
5/27/2013
6/1/2013
6/6/2013
6/11/2013
6/16/2013
6/21/2013
6/26/2013
7/1/2013
7/6/2013
7/11/2013
7/16/2013
7/21/2013
7/26/2013
7/31/2013
8/5/2013
8/10/2013
8/15/2013
8/20/2013
8/25/2013
8/30/2013
9/4/2013
9/9/2013
9/14/2013
9/19/2013
9/24/2013
9/29/2013
10/4/2013
10/9/2013
10/14/2013

Surface Water Treatment Results

Total Aluminum				
Sampling Date	Influent Concentration (ug/L)	Effluent Concentration (ug/L)	Reduction (ug/L)	Percent Reduction
5/7/2013	62	720	-658.00	-1061%
5/28/2013	220	880	-660.00	-300%
6/4/2013	390	1100	-710.00	-182%
6/14/2013	160	760	-600.00	-375%
6/26/2013	140	780	-640.00	-457%
7/16/2013	110	2800	-2690.00	-2445%
7/31/2013	280	1100	-820.00	-293%
8/15/2013	320	1500	-1180.00	-369%
9/6/2013	240	17000	-16760.00	-6983%
9/12/2013	260	13000	-12740.00	-4900%
9/26/2013	290	28000	-27710.00	-9555%
10/2/2013	320	5100	-4780.00	-1494%
10/11/2013	630	1100	-470.00	-75%
10/17/2013	990	6200	-5210.00	-526%

J: Detected but below the Method Reporting Limit
ND: Not Detected

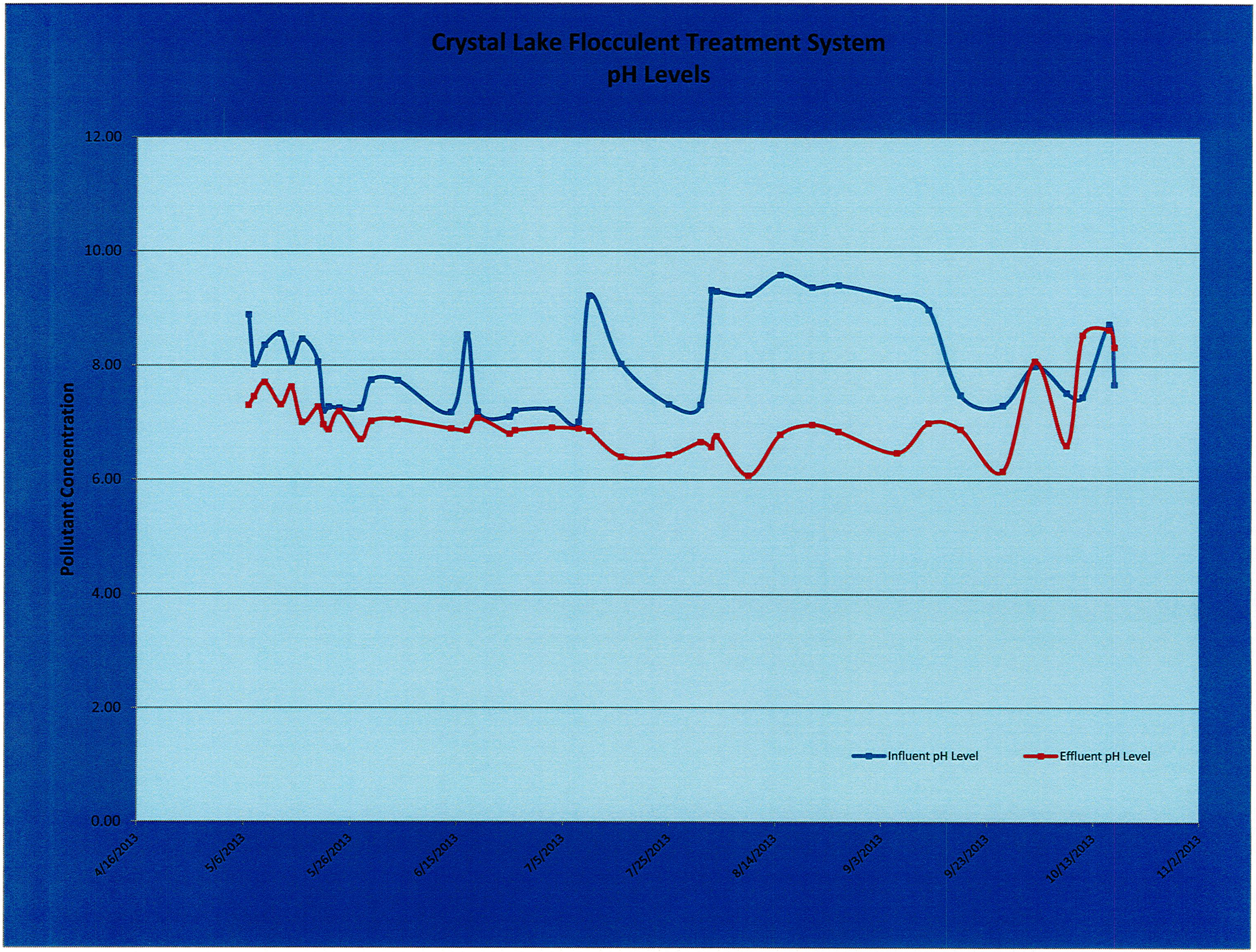


Crystal Lake Flocculent Treatment System
Total Aluminum Concentration
Influent Concentration (ug/L)
Effluent Concentration (ug/L)
Pollutant Concentration
29000
24000
19000
14000
9000
4000
-1000
5/7/2013
5/12/2013
5/17/2013
5/22/2013
5/27/2013
6/1/2013
6/6/2013
6/11/2013
6/16/2013
6/21/2013
6/26/2013
7/1/2013
7/6/2013
7/11/2013
7/16/2013
7/21/2013
7/26/2013
7/31/2013
8/5/2013
8/10/2013
8/15/2013
8/20/2013
8/25/2013
8/30/2013
9/4/2013
9/9/2013
9/14/2013
9/19/2013
9/24/2013
9/29/2013
10/4/2013
10/9/2013
10/14/2013

Surface Water Treatment Results

pH Levels			
Sampling Date	Influent pH Level	Effluent pH Level	Change in pH
5/7/2013	8.88	7.30	1.58
5/8/2013	8.01	7.45	0.56
5/10/2013	8.350	7.700	0.65
5/13/2013	8.550	7.310	1.24
5/15/2013	8.060	7.620	0.44
5/17/2013	8.460	7.000	1.46
5/20/2013	8.060	7.270	0.79
5/21/2013	7.200	6.960	0.24
5/22/2013	7.270	6.870	0.40
5/24/2013	7.250	7.190	0.06
5/28/2013	7.250	6.700	0.55
5/30/2013	7.740	7.020	0.72
6/4/2013	7.730	7.050	0.68
6/14/2013	7.180	6.890	0.29
6/17/2013	8.540	6.860	1.68
6/19/2013	7.190	7.080	0.11
6/25/2013	7.10	6.80	0.30
6/26/2013	7.21	6.86	0.35
7/3/2013	7.23	6.91	0.32
7/8/2013	7.01	6.89	0.12
7/10/2013	9.220	6.850	2.37
7/16/2013	8.030	6.400	1.63
7/25/2013	7.320	6.430	0.89
7/31/2013	7.310	6.660	0.65
8/2/2013	9.320	6.570	2.75
8/3/2013	9.300	6.760	2.54
8/9/2013	9.240	6.070	3.17
8/15/2013	9.590	6.790	2.80
8/21/2013	9.370	6.960	2.41
8/26/2013	9.41	6.84	2.57
9/6/2013	9.19	6.47	2.72
9/12/2013	8.98	6.99	1.99
9/18/2013	7.48	6.88	0.60
9/26/2013	7.30	6.15	1.15
10/2/2013	7.99	8.08	-0.09
10/8/2013	7.52	6.60	0.92
10/11/2013	7.45	8.54	-1.09
10/16/2013	8.73	8.63	0.10
10/17/2013	7.67	8.33	-0.66
Averages:	**8.07**	**7.04**	**1.02**

pH monitoring was performed on site using a Hach HQ440d meter.


Crystal Lake Flocculent Treatment System
pH Levels
Pollutant Concentration
12.00
10.00
8.00
6.00
4.00
2.00
0.00
4/16/2013
5/6/2013
5/26/2013
6/15/2013
7/5/2013
7/25/2013
8/14/2013
9/3/2013
9/23/2013
10/13/2013
11/2/2013
Influent pH Level
Effluent pH Level

Reagent Usage

Aluminum Sulfate Dosage		
Operation date	Total Aluminum	Total Alum Used (gal)
5/31/2013	891.600	427.611
6/30/2013	1567.000	751.533
7/31/2013	2998.8	1438.224
8/31/2013	3416	751.520
9/30/2013	2774.400	610.368
10/20/2013	1786.200	392.964

Reagent Usage

Sodium Hydroxide Dosage		
Operation date	Reagent dosage	Sodium Hydroxide used (gal)
5/31/2013	0.00	0.00
6/30/2013	0.00	0.00
7/31/2013	0.00	0.00
8/31/2013	0.00	0.00
9/30/2013	0.00	0.00
10/20/2013	0.00	0.00

Crystal Lake 2013 Water Quality Sampling and Aquatic Vegetation Surveys

Shingle Creek Watershed Management Commission

Hennepin County, MN

Prepared For: **Shingle Creek Watershed Management Commission**

Date: **May 2013**

Prepared By: **Wenck Associates, Inc.**
1800 Pioneer Creek Ctr
Maple Plain, MN 55359

Wenck
Engineers • Scientists

Introduction

Crystal Lake is located in the City of Robbinsdale in Hennepin County (Figure 1). Crystal Lake is a highly used recreational water body with an active fishery as well as other aesthetic values. Crystal Lake has an approximate surface area of 89 acres, with a maximum depth of 39 feet and an average depth of 10 feet. The drainage area to the lake is 1,237 acres of fully developed urban and suburban land. The drainage area is almost entirely in the City of Robbinsdale, with some contribution from the City of Minneapolis. Crystal Lake does not have a natural outle; a pumping station is used under high water conditions to discharge into the City of Minneapolis storm sewer system. The storm sewer discharges into Shingle Creek, which ultimately discharges to the Mississippi River. Water quality in Crystal Lake is considered poor and not supportive of recreational activities, with frequent algal blooms.

Crystal Lake was placed on Minnesota's 303(d) list of impaired waters for nutrients (total phosphorus) in 2002. A Total Maximum Daily Load (TMDL) study and Implementation Plan were completed and approved in 2008.

The Implementation Plan recommended future monitoring activities to assess progress toward achieving the TMDL and state water quality standards. Those activities were incorporated into the Shingle Creek Watershed Management Commission's Third Generation Watershed Management Plan 2013-2022, including periodic intensive water quality monitoring, aquatic vegetation surveys, and fish sampling coordinated with the Department of Natural Resources. This report details the results of intensive water quality sampling and aquatic vegetation surveys conducted in 2013 in anticipation of the five year review of TMDL progress. Ongoing volunteer surface water quality sampling is detailed in the Commission's Annual Water Quality report.

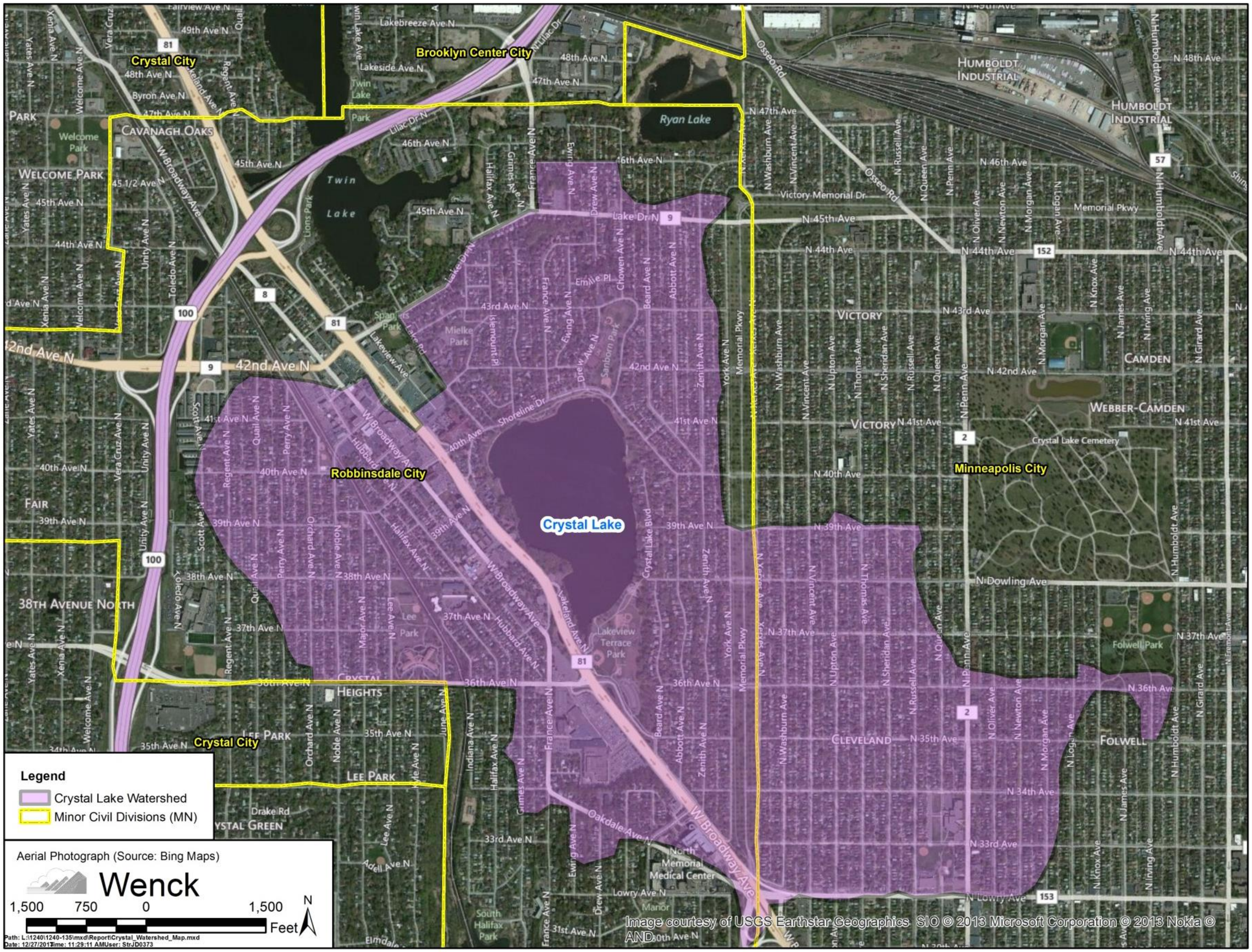


Figure 1. Crystal Lake watershed

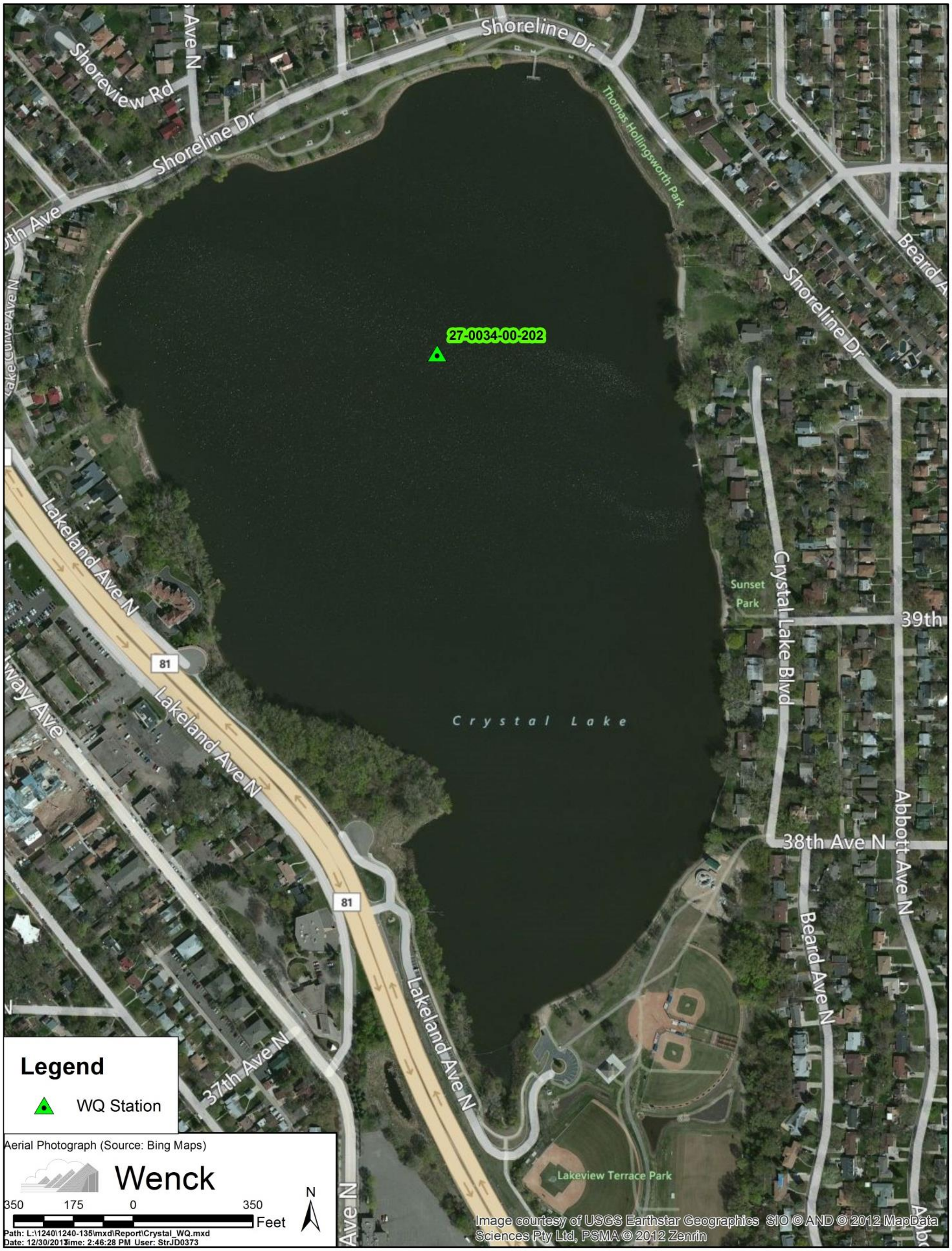


Figure 2. Crystal Lake bathymetry and historic water quality monitoring station

Water Quality Sampling Methods

Water quality in Minnesota lakes is often evaluated using three associated parameters: total phosphorus, chlorophyll-a, and Secchi depth. Total phosphorus is typically the limiting nutrient in Minnesota's lakes meaning that algal growth will increase with increases in phosphorus. However, there are cases where phosphorus is widely abundant and the lake becomes limited by nitrogen or light availability. Chlorophyll-a is the primary pigment in aquatic algae and has been shown to have a direct correlation with algal biomass. Since chlorophyll-a is a simple measurement, it is often used to evaluate algal abundance rather than expensive cell counts. Secchi depth is a physical measurement of water clarity, measured by lowering a black and white disk until it can no longer be seen from the surface. Higher Secchi depths indicate less light refracting particulates in the water column and better water quality. Conversely, high total phosphorus and chlorophyll-a concentrations point to poorer water quality and thus lower water clarity. Measurements of these three parameters are interrelated and can be combined into an index that describes water quality.

Water quality sampling was conducted by Wenck staff at the Crystal Lake monitoring site (27-0034-00-202) in 2013 (Figure 2). Water depth at the Crystal Lake monitoring site is approximately 36 feet (11 meters) and near the basin's deep hole. Surface samples were collected bi-weekly from late May through early October for total phosphorus (TP), Secchi depth and chlorophyll-a.

Water Quality Sampling Results

Summer TP concentrations in 2013 exceeded the 40 µg/L standard for deep lakes on every sampling event during the 2013 growing season (Figure 3). TP concentrations ranged between 53 and 80 µg/L during the summer growing season. The highest TP value in 2013 was 95 µg/L and was recorded in early October when lake began to turn over and deep, hypolimnetic water began mixing with surface waters. Chlorophyll-a concentrations exceeded the 14 µg/L standard for deep lakes on seven of the eight summer growing season sampling events in 2013 (Figure 4). Chlorophyll-a measurements were high beginning in late June through September and then began to decrease in early October. Secchi depth in general follows the same trend as chlorophyll-a. Water clarity in Crystal Lake was poor and never met deep lake standards throughout the entire 2013 sampling season (Figure 5).

Crystal Lake historic data indicate TP concentrations may have decreased slightly since the 1994 and 1997 sampling seasons when average summer concentrations were 234 µg/L and 239 µg/L, respectively (Figure 6). Since 2001, average summer TP has fluctuated between 42-114 µg/L but is still consistently above the 40 µg/L deep lake standard. Historic chlorophyll-a and transparency data indicate no clear trends and have failed to meet water quality standards over the last 20 years (Figures 7 and 8).

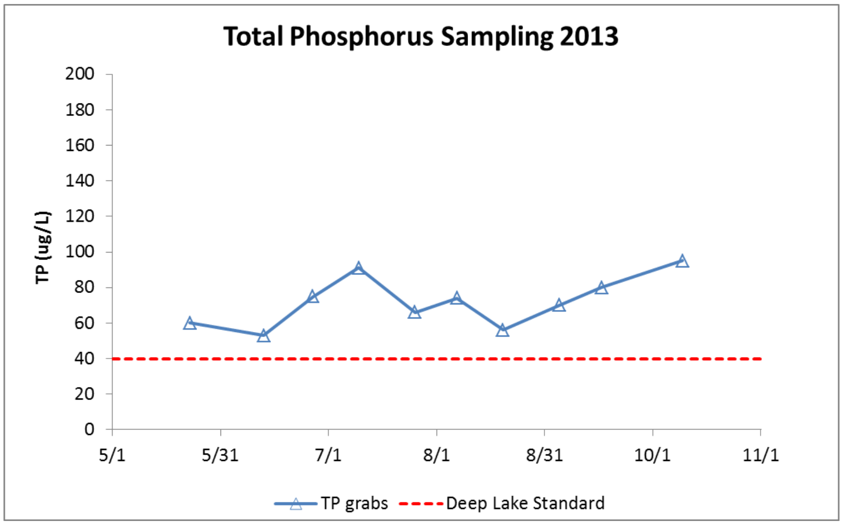


Figure 3. Crystal Lake 2013 TP

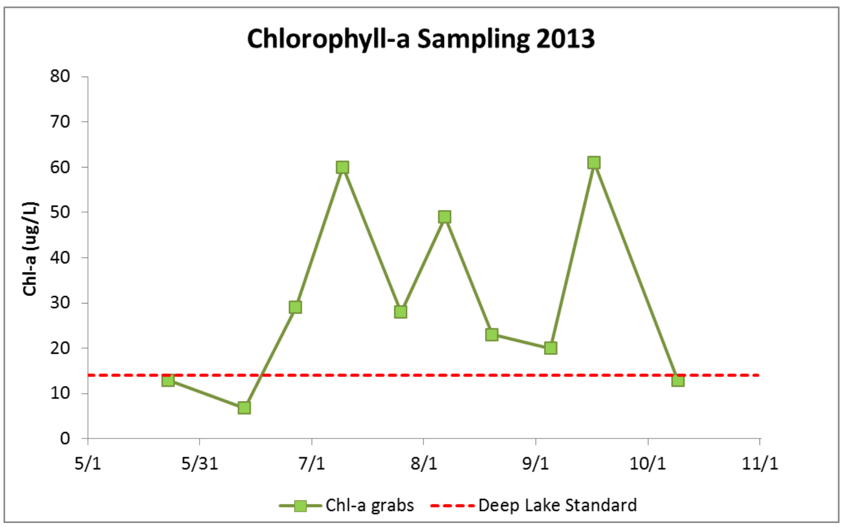


Figure 4. Crystal Lake 2013 chlorophyll-a

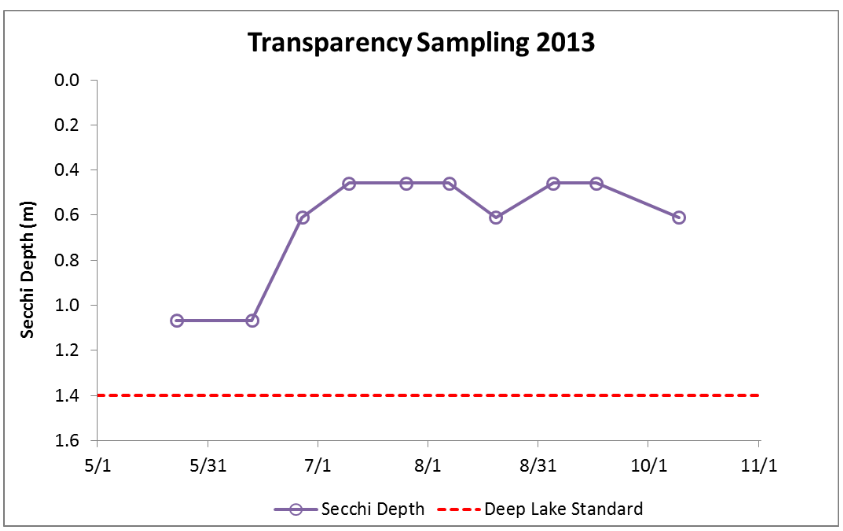


Figure 5. Crystal Lake 2013 transparency

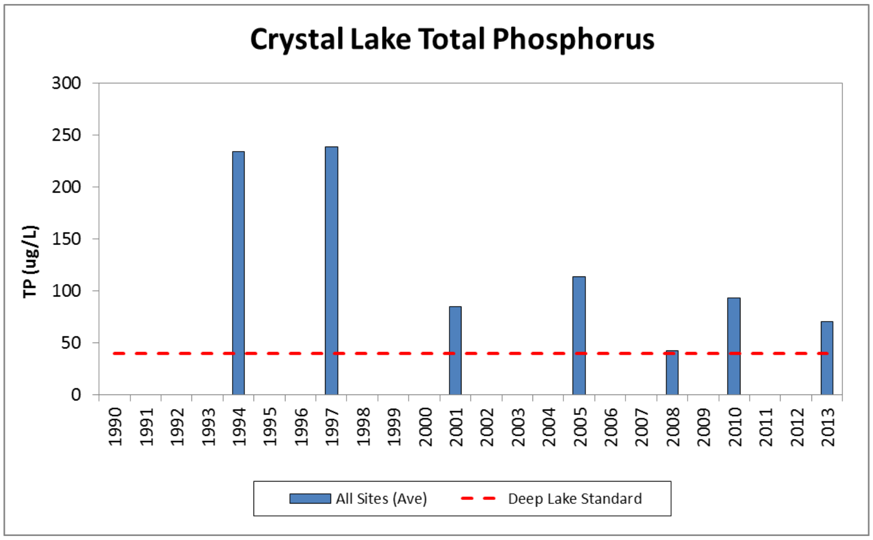


Figure 6. Crystal Lake historic average summer growing season (June through September) TP

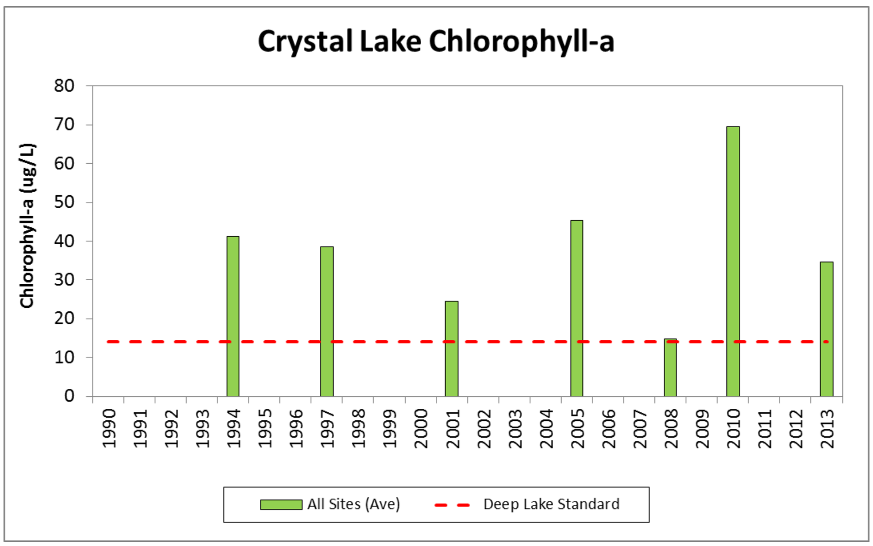


Figure 7. Crystal Lake historic average summer growing season chlorophyll-a

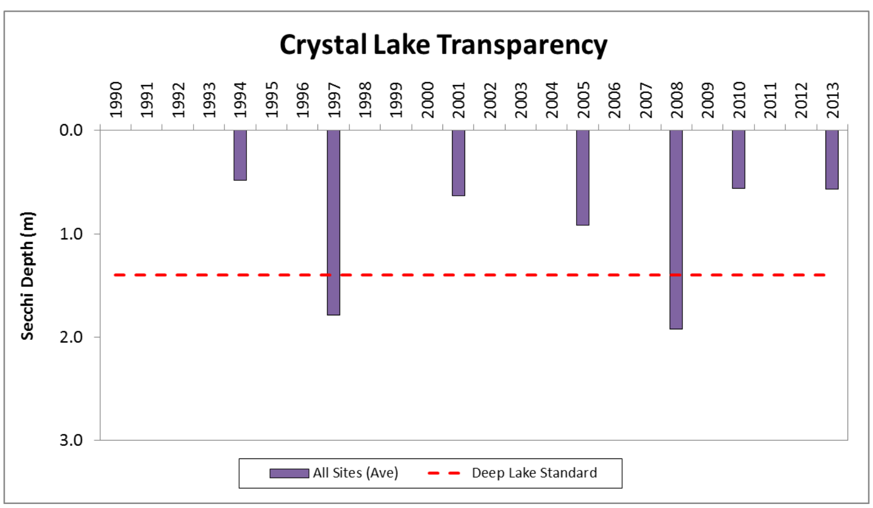


Figure 8. Crystal Lake historic average summer growing season Secchi depth

Aquatic Vegetation Survey Methods

A point-intercept survey using methodology developed by the Minnesota Department of Natural Resources (DNR) was conducted on June 18, 2013 and in late summer on September 6, 2013. Point-intercept sample points were established in GIS across the entire lake basin using a 50 meter grid file (Figure 9). A total of 126 points were sampled during the June survey, and 124 points were sampled during the September survey. The surveyed grid was downloaded onto a GPS unit that was used to navigate to each sample point during the survey. One side of the boat was designated as the sampling area. Water depth was recorded at each sample point in increments estimated to the nearest tenth of a foot using a survey range pole and electronic depth finder.

Wenck staff identified all plant species found within a one meter squared sample site at each survey point. A weighted sampling hook attached to a rope was used to survey vegetation not visible from the surface. All vegetation species observed were identified to the species level where possible. Species abundances rankings were also visually assessed and recorded at each monitoring point using a 0-5 ranking scale described in Table 1. Water clarity was also recorded during each survey by measuring the depth at which a Secchi disk was visible when lowered into the water.

The late summer survey was conducted to assess the lake's overall native plant community and diversity during the heart of the summer growing season. The early summer survey was conducted specifically to estimate the distribution and abundance of curly-leaf pondweed. Curly-leaf pondweed is a non-native plant species that can outcompete native plant species and disrupt lake ecosystems by changing the dynamics of internal phosphorus loading. Curly-leaf pondweed is a perennial, submersed aquatic plant that was first noted in Minnesota around 1910. Curly-leaf pondweed has the ability to grow slowly throughout the winter, even under thick ice and snow cover. Thus by the time other species start growing in the spring, curly-leaf plants are large enough to block light penetration to the bottom. By late spring, curly-leaf pondweed can form dense surface mats which interfere with recreation activities. By mid-summer, these dense mats senesce and die back, releasing nutrients that can contribute to undesirable algae blooms. Before curly-leaf pondweed plants die back, they form hardened stem tips called turions, which serve the function of vegetative reproduction. These turions sprout in the fall and begin the plant's cycle again.

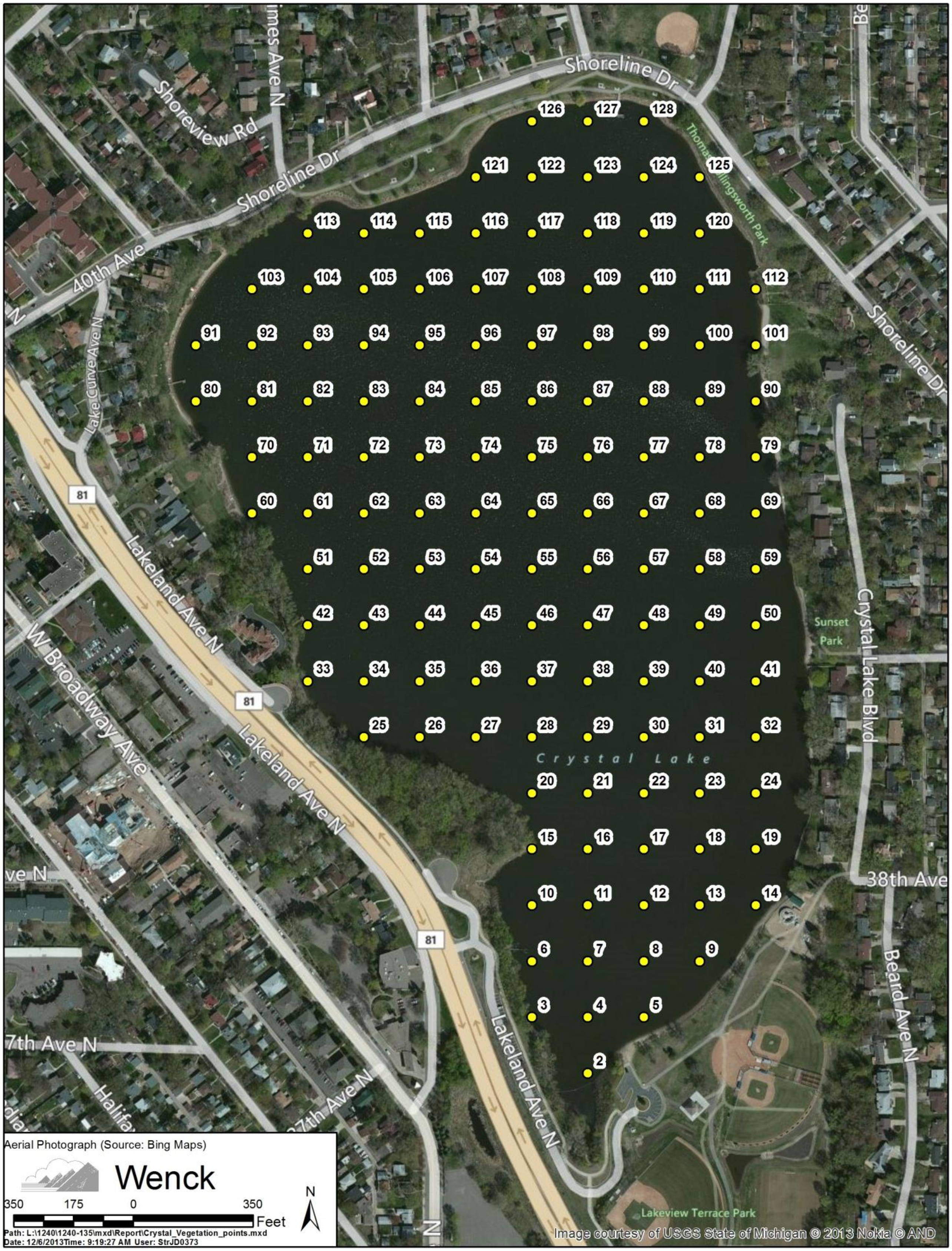
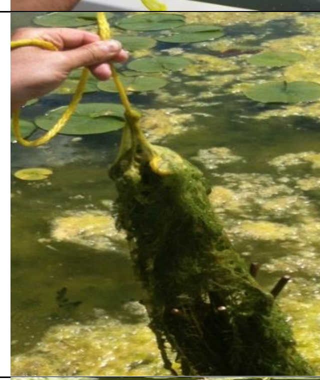


Figure 9. Point intercept survey points

Table 1. Description of species abundance rankings.

Ranking	Description	Visual
0	None present	
1	Species present, low abundance, one or two noted	
2	Species present, low abundance growth limited to bottom sediments	
3	Species present, moderate abundance growing at or near surface	
4	Species present, high abundance growing to surface	
5	Species present, extreme abundance matted growth on surface	

Survey Results

Following each survey, the data was entered into a spreadsheet and frequency of occurrence was calculated for each species. The spreadsheet was integrated into GIS to create maps showing the extent of submergent aquatic vegetation and curly leaf pondweed in the lake.

Number of Species Recorded and Frequency of Occurrence

The frequency of occurrence of each species during each survey is summarized in Table 2. Vegetation was found at only 3 of 126 (2%) sampling sites during the June 18, 2013 survey (Figure 10). In areas of the lake less than 15 feet deep, vegetation was found at 3 of 91 (3%) sites. Three species of aquatic vegetation were documented at sample stations during the June survey. The maximum depth at which vegetation was found during this survey was 6 feet. In general, vegetation was sparse and was present at only a few locations. Moreover, abundance rankings at the three sites with vegetation was one, which indicates very low density and biovolume. Secchi depth was measured at 1.1 meters (3.5 feet) during the survey which was the best transparency noted in 2013 (Figure 5).

Vegetation was found at only 2 of 124 (2%) sampling sites during the September 6, 2013 survey (Figure 11). In areas of the lake less than 15 feet deep, vegetation was found at 2 of 89 (2%) sites. One species of aquatic vegetation was documented at two sample stations during the September 6, 2013 survey. The maximum depth at which vegetation was found was 3 feet. Secchi depth was measured at 0.5 meters (1.5 feet) during this survey which was the lowest transparency reading in 2013.

The only species observed during the June 2013 survey were curly-leaf pondweed (1%), white waterlily (1%) and yellow waterlily (1%). Curly-leaf pondweed was observed at only one sampling site during the June survey. The only species observed in the September was white waterlily (2%). As expected, curly-leaf pondweed was not present at any of the survey locations during the August survey. Eurasian milfoil, another non-native invasive species, was not observed during either of the 2013 surveys.

Table 2. Frequency of occurrence.

Common Name	Scientific Name	Percent Occurrence	
		June 18, 2013	September 6, 2013
Curly-leaf pondweed	*Potamogeton crispus*	1%	0%
White waterlily	*Nymphaea ordorata*	1%	2%
Yellow waterlily	*Nymphaea mexicana*	1%	0%

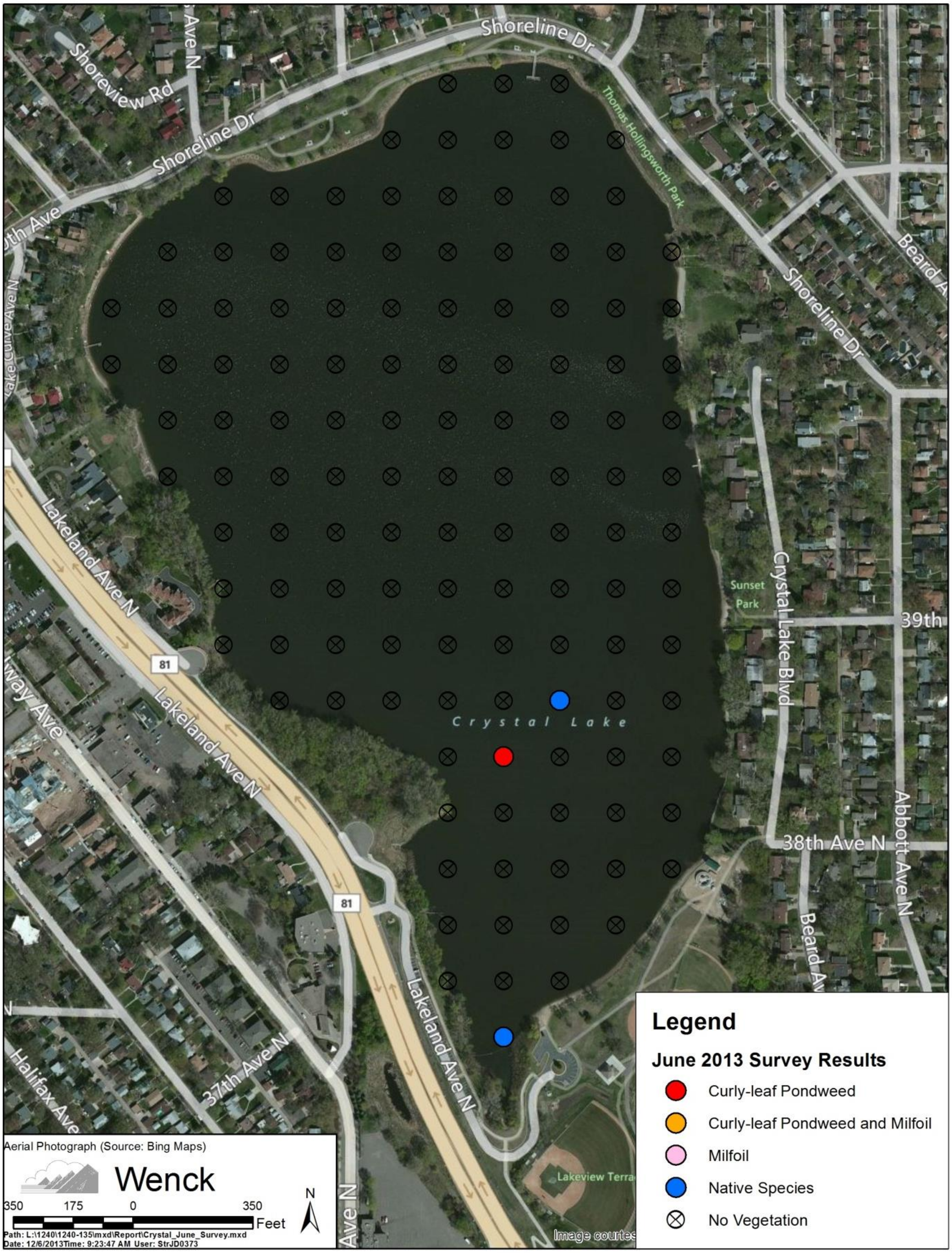


Figure 10. June 18, 2013 survey results.

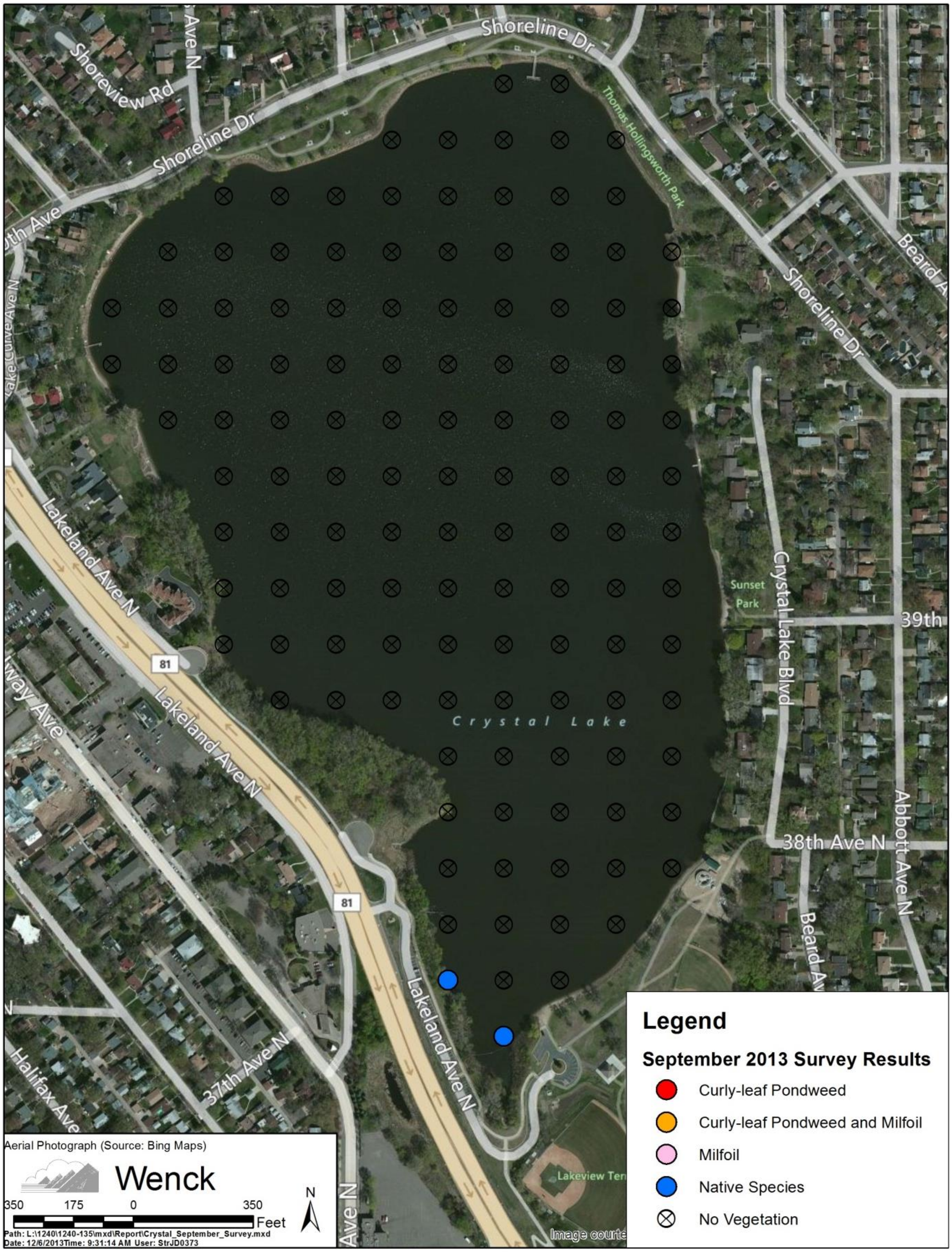


Figure 11. September 6, 2013 survey results.

Distribution of Non-native and Native Plant Communities

Curly-leaf pondweed is a perennial non-native submergent plant that has been become more abundant in certain lakes throughout the Shingle Creek watershed and the Twin Cities metropolitan area. As discussed previously, the presence of dense curly-leaf pondweed has been linked to increased nutrient concentrations and periodic poor water quality in lakes due to the plant's unique life cycle. There were no formal vegetation surveys conducted in Crystal Lake prior to 2013 so it is difficult to assess the history of curly-leaf pondweed and other plant species in the lake. Anecdotal evidence from the Crystal Lake TMDL Task Force is that rooted aquatic plants used to pose a nuisance problem on the north end of the lake around the fishing pier and both Eurasian milfoil and curly-leaf pondweed has been observed on Crystal Lake in the past. Approximately 8 acres along the northwest shoreline was shoreline was treated with herbicide to reduce curly-leaf pondweed in 2001, 2002 and 2004. Approximately 4 acres was treated again in 2003. However, no historic data are available describing the relative abundance of curly-leaf and other plant species in Crystal Lake. Curly-leaf pondweed was observed in low abundance at only one sampling location during the June 2013 survey. Thus, curly-leaf pondweed no longer appears to be a problem in Crystal Lake at this time.

Beside curly-leaf pondweed, white waterlily and yellow waterlily were the only other species observed during in Crystal Lake in 2013 (Figure 12). Overall, Crystal Lake suffers from an extreme lack of submerged vegetation and does not currently support any native pondweed species common in healthy shallow and deep lakes throughout Minnesota.

Figure 12. White waterlily in Crystal Lake

Figure 13. Cyrstal Lake littoral area with no vegetation

Conclusions and Recommendations

- Total phosphorus levels in Crystal Lake have improved since the mid/late 1990's. However, the response variables, chlorophyll-a and transparency, show no clear trends over the last 20 years and all three water quality parameters have consistently exceeded state water quality standards during this time. Water quality monitoring in Crystal Lake should continue as management practices are implemented in the lake and throughout the watershed.

- Submerged aquatic plants were found to depths of 6.0 feet. Crystal Lake suffers from an extreme lack of submerged vegetation as only 2% of the sample points in the littoral area of the lake (<15 feet) had at least one species of submergent vegetation during the June and September 2013 surveys. Upper Twin Lake is a shallow lake with a maximum depth of 12 feet and 100% littoral (<15 feet) coverage.

- In the early 2000's, curly-leaf pondweed and Eurasian milfoil were abundant along the north end of the lake and chemical treatments were performed from 2001-2004. No curly-leaf pondweed or Eurasian milfoil were observed during the June and September 2013 vegetation surveys suggesting these treatments may have been successful in reducing species abundance in this portion of the lake. It is important to point out, however, that no native submerged aquatic vegetation species were observed in the north end of Crystal Lake and throughout most of the lake's littoral zone in 2013, which is problematic. Submerged aquatic vegetation play a critical role in water quality especially in shallow areas of lakes providing habitat for fish, stabilizing sediments preventing wind resuspension and turbid water, and represent a food source and habitat for macroinvertebrates. Crystal Lake's lack of submerged aquatic vegetation likely inhibits good water quality in the lake.

- Restoration of submerged aquatic vegetation typically involves whole-lake drawdown to consolidate sediments and invigorate the native seed bank. However, whole lake draw down may be extremely difficult in Crystal Lake due to its littoral depth, recreational uses and urban setting. Consequently, the best approach for restoring native vegetation is to improve water clarity and control the spread of invasive vegetation species so that the native vegetation can re-establish.

Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for Profundal Sediments in Crystal and Margaret Lake, Minnesota

14 May, 2008

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OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus release from sediments under laboratory-controlled oxic and anoxic conditions and to quantify mobile and refractory phosphorus fractions in profundal sediments of Crystal and Margaret Lake, Minnesota.

APPROACH

Laboratory-derived rates of phosphorus release from sediment under oxic and anoxic conditions: Duplicate sediment cores were collected by Wenck Associates from a shallow and deep location in Crystal Lake for determination of rates of phosphorus release from sediment under oxic and anoxic conditions. The cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water from the lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 ^{o}C) for a three week period. The oxidation-reduction environment in the overlying water was controlled by gently bubbling nitrogen (anoxic) or air (oxic) through an air stone placed just above the sediment surface in each system.

Water samples for soluble reactive phosphorus were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). Sampling was conducted at daily intervals for 5 days, then every other day for an additional 14 days. The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive phosphorus was measured colorimetrically using the ascorbic acid method (APHA 1998). Rates of phosphorus release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in soluble reactive phosphorus mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Profundal sediment chemistry: One additional core was collected at the same locations in Crystal Lake and from the north and south basin of Margaret Lake for determination of sediment physical-chemical characteristics and sediment phosphorus fractionation. The upper 10 cm was removed from each core for analysis of moisture content (%), sediment density (g/mL), loss on ignition (i.e., organic matter content, %), loosely-bound phosphorus, iron-bound phosphorus, aluminum-bound phosphorus, calcium-bound phosphorus, labile and refractory organic phosphorus, total phosphorus, total iron, and total calcium (all expressed at mg/g). A known volume of sediment was dried at 105 ^{o}C for determination of moisture content and sediment density and ashed at 500 ^{o}C for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Additional sediment was dried to a constant weight, ground, and digested for analysis of total phosphorus, iron, and calcium using standard methods (Plumb 1980; APHA 1998). Phosphorus fractionation was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable phosphorus (loosely-bound P), bicarbonate-dithionite-extractable phosphorus (i.e., iron-bound P), sodium hydroxide-extractable phosphorus (i.e., aluminum-bound P), and hydrochloric acid-extractable phosphorus (i.e., calcium-bound P). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P. Refractory organic phosphorus was estimated as the difference between total phosphorus and the sum of the other fractions.

RESULTS AND INTERPRETATION

Phosphorus mass in the overlying water column of oxic sediment systems exhibited an initial decline over the first two days of incubation, which may have been attributable to the development of an oxidized microzone and temporary sorption of phosphorus (Figure 1; Penn et al. 2000). Phosphorus mass accumulation occurred in the overlying water column after day 2; however, the oxic release rate was minor for both Crystal Lake stations (Table 1). Duplicate oxic release rates were similar for the shallow station, resulting in a relatively low standard error. At the deep station, oxic release rates were much higher for replicate 1 versus 2. Nevertheless, these rates were negligible compared to those observed under anoxic conditions (Figure 1). Phosphorus mass increased rapidly over days 1-4 in sediment systems incubated under anoxic conditions. After day 4, the rate of phosphorus mass accumulation declined and reached an asymptote by day 18 for sediment cores collected at the shallow station. Phosphorus mass accumulation was very rapid in the deep station sediment system subjected to anoxic conditions. Gas production (most likely methane) during incubation resulted in separation of deep station sediments into multiple layers after day 4 and disruption of the overlying water column. The mean anoxic release rate was 6.4 $mg \cdot m^{-2} \cdot d^{-1}$ and 19.8 $mg \cdot m^{-2} \cdot d^{-1}$ for the shallow and deep station, respectively (Table 1). Anoxic release rates were within ranges reported by Nürnberg (1988; Figure 2).

Crystal Lake shallow station sediments exhibited a much lower moisture content, lower loss-on-ignition organic matter, and higher sediment density than deep station sediments, suggesting coarser-grained particle sizes typically found in shallow erosional zones (i.e., higher sand content; Table 2). In contrast, moisture content exceeded 90%, while sediment density was very low for deep station sediments, indicating fine-grained, flocculent material. Loss-on-ignition organic matter content was relatively high at 33.3% for deep station sediments. Total sediment phosphorus, iron, and calcium concentrations reflected differences in physical characteristics and organic matter content as they were greater at the deep versus shallow station (Table 2). The Fe:P ratio was relatively high for both stations (i.e., > 10), suggesting regulation of phosphorus release by iron hydroxides under oxic conditions (Jensen et al., 1992). This pattern was in agreement with the very low oxic release rates measured for Crystal Lake sediments.

Biologically-labile (i.e., subject to recycling; loosely-bound, iron-bound, and labile organic) phosphorus accounted for ~ 21% and 40% of the total phosphorus in sediments at the shallow and deep station, respectively (Table 1; Figure 3). Redox-sensitive phosphorus (i.e., loosely-bound and iron-bound phosphorus) was dominated by the iron-bound fraction (Figure 3) and represented ~13% and 26% of the total sediment phosphorus at the shallow and deep station, respectively (Table 2). This functionally defined fraction has been correlated with P flux out of sediment under both oxic and anoxic conditions (Boström et al. 1982; Ostrofsky 1987; Ostrofsky et al. 1989; Nürnberg 1988; Petticrew and Arocena 2001). Redox-sensitive phosphorus versus anoxic release rates from the present study (Figure 4) were comparable to published regression relationships developed by Nürnberg (1988), suggesting that anoxia, reduction of iron, and desorption of P were drivers in internal P loading. Refractory forms of sediment phosphorus (i.e., subject to burial; aluminum-bound, calcium-bound, and refractory organic phosphorus) were dominated by the refractory organic phosphorus fraction, accounting for 79% and 60% of the total phosphorus for the shallow and deep station, respectively (Figure 3).

Sediment cores collected in the north and south basin of Margaret Lake exhibited very high moisture content, low sediment density, and a loss-on-ignition organic matter content of 26 to 31% (Table 2). Total phosphorus concentrations were very high relative to total iron, resulting in an Fe:P ratio < 10. This pattern suggested that phosphorus bound to iron compounds was approaching saturation (i.e., low number of available binding sites; Jensen et al. 1992). Iron-bound phosphorus accounted for > 40% of the total phosphorus (Table 1; Figure 5) and was an order of magnitude greater than values reported for a variety of lakes in North America (Nürnberg 1988). Although anoxic release rates were not measured at the time of sediment core collection, high redox-sensitive phosphorus concentrations suggested the possibility of high anoxic release rates in this lake (Nürnberg 1988). However, concentrations observed for Margaret Lake sediments fell well beyond the range of values used in the redox-sensitive phosphorus versus anoxic release rate regression equation developed by Nürnberg (1988; i.e., Figure 4 of this report). There is evidence that these relationships are nonlinear at higher redox-sensitive phosphorus concentrations (i.e., an asymptote is approached; James, unpublished). Thus, prediction of the anoxic release rate from redox-sensitive phosphorus is uncertain for Margaret Lake sediments.

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Table 1. Rates of phosphorus (P) release (standard error in parentheses; n=2) and concentrations of biologically labile and refractory P in sediments. DW = dry mass, FW = fresh mass.

Lake	Rates of P Release		Redox-sensitive and biologically labile P				Refractory P		
	Oxic ($mg\ m^{-2}\ d^{-1}$)	Anoxic ($mg\ m^{-2}\ d^{-1}$)	Loosely-bound P (mg/g)	Iron-bound P (mg/g DW)	Iron-bound P (mg/g FW)	Labile organic P (mg/g)	Aluminum-bound P (mg/g)	Calcium-bound P (mg/g)	Refractory organic P (mg/g)
Crystal Shallow	0.01 (0.01)	6.4 (1.9)	0.006	0.046	0.017	0.036	0.042	0.121	0.151
Crystal Deep	0.4 (0.3)	19.8 (0.6)	0.014	0.568	0.036	0.308	0.236	0.212	0.939
Margaret N			0.149	3.253	0.244	0.044	1.607	0.131	2.216
Margaret S			0.253	3.407	0.388	0.043	1.562	0.120	1.919

Table 2. Sediment physical-chemical characteristics. Redox phosphorus (P) represents the sum of the loosely-bound and iron-bound P fractions (Table 1). Fe = iron, Ca = calcium.

Lake	Moisture Content (%)	Density (g/mL)	Loss-on-ignition (%)	Total P (mg/g)	Redox P (mg/g)	Redox P (%)	Total Fe (mg/g)	Total Ca (mg/g)	Fe:P
Crystal Shallow	64.2	0.482	4.4	0.402	0.052	12.9	8.238	10.406	20.5
Crystal Deep	93.6	0.067	33.3	2.277	0.582	25.6	25.646	25.866	11.3
Margaret N	92.5	0.082	31.1	7.356	3.402	46.2	39.268	13.544	5.3
Margaret S	88.6	0.126	26.4	7.261	3.660	50.4	43.274	14.503	6.0

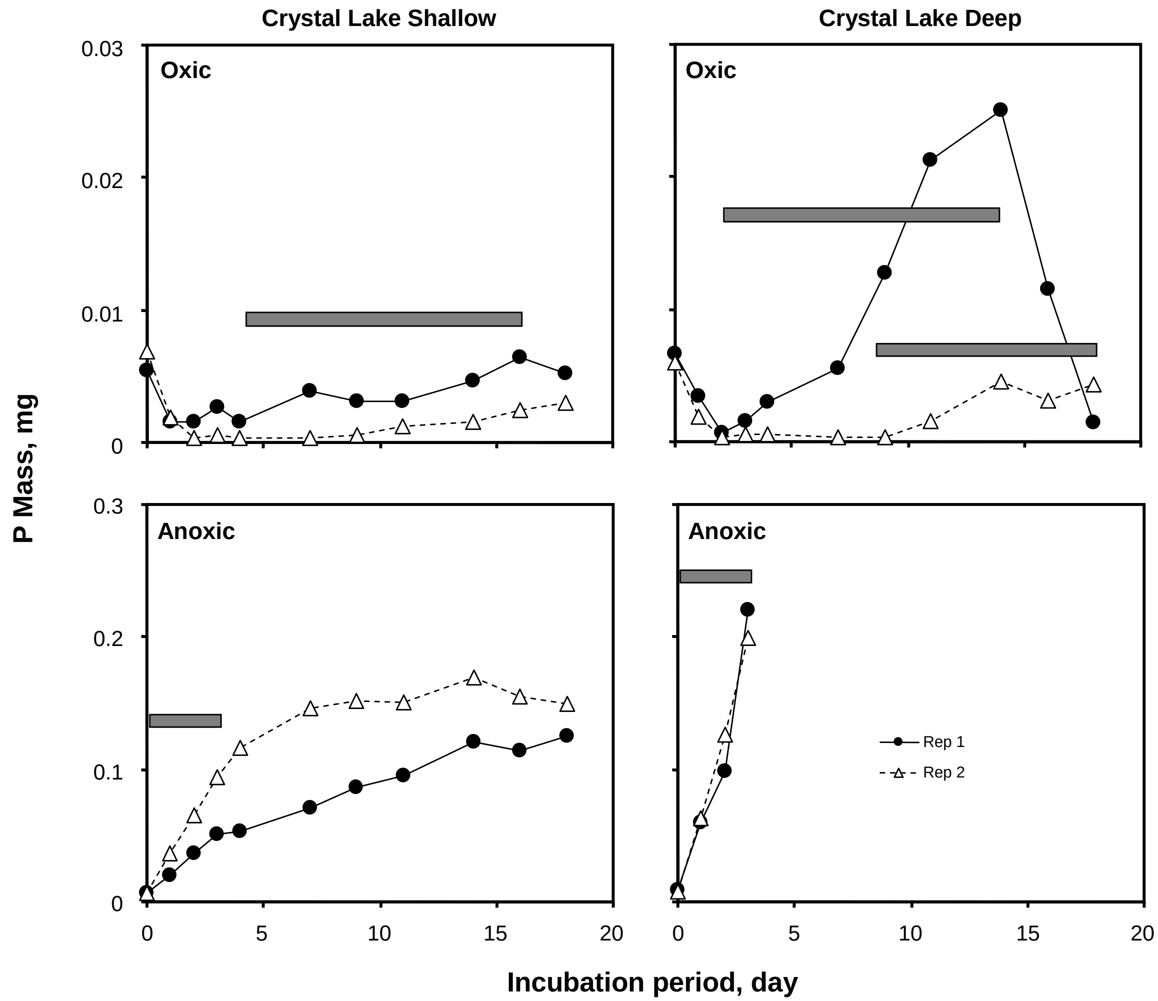


Figure 1. Changes in soluble reactive phosphorus (P) mass in the overlying water column versus time in Crystal Lake sediment incubation systems. Horizontal bars represent the period of linear increase in P mass used to estimate release rates.

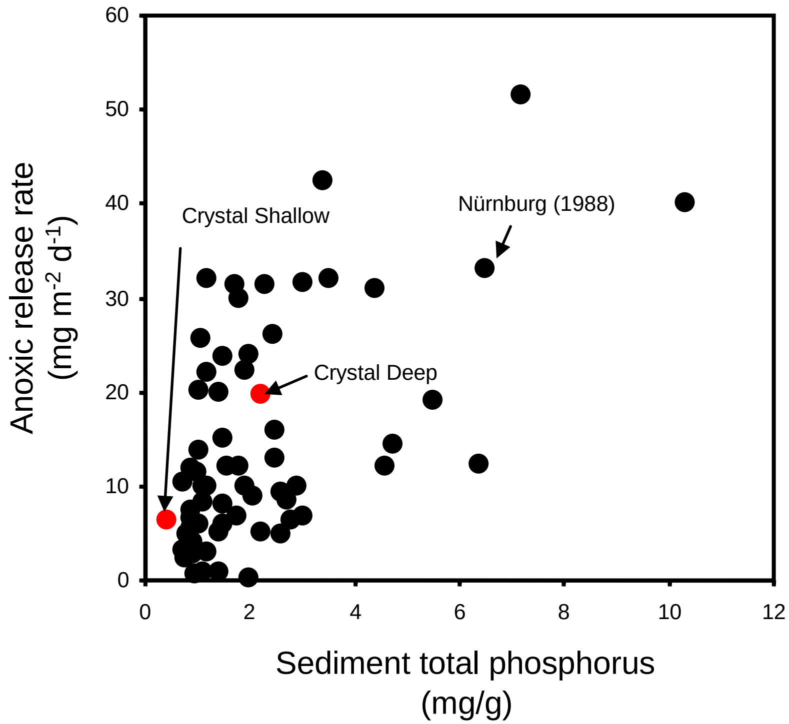
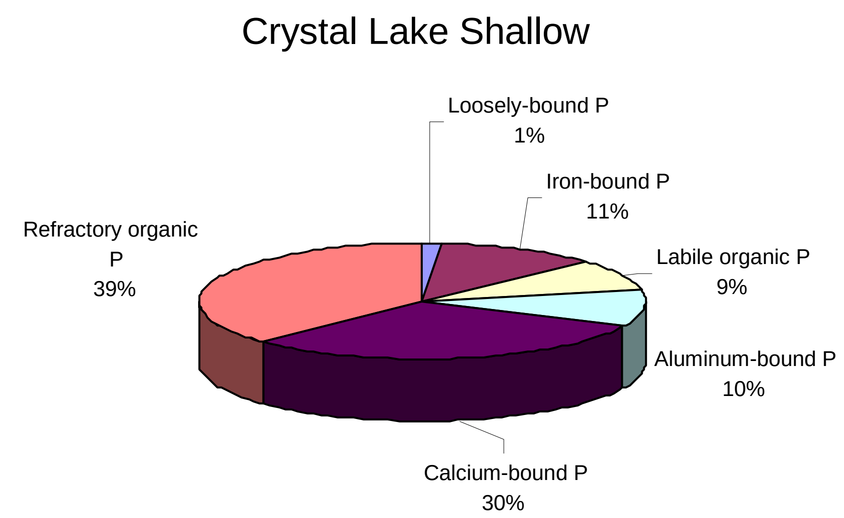


Figure 2. The anoxic release rate versus sediment total phosphorus from Nürnburg (1988). Solid red circles represent results for Crystal Lake sediment.



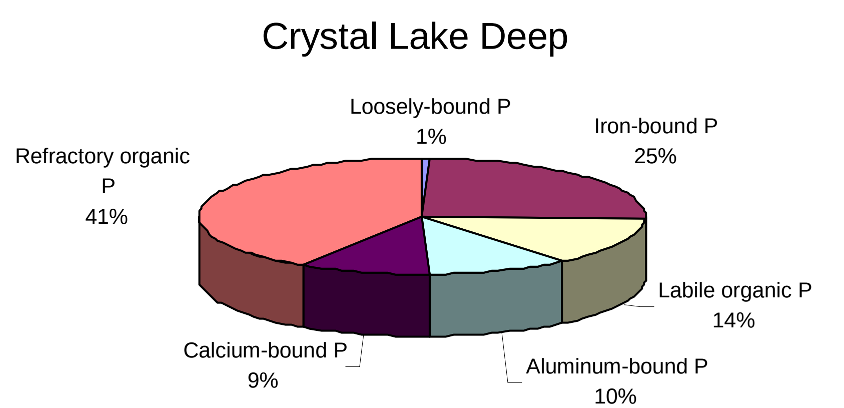


Figure 3. Sediment phosphorus (P) composition for Crystal Lake sediment.

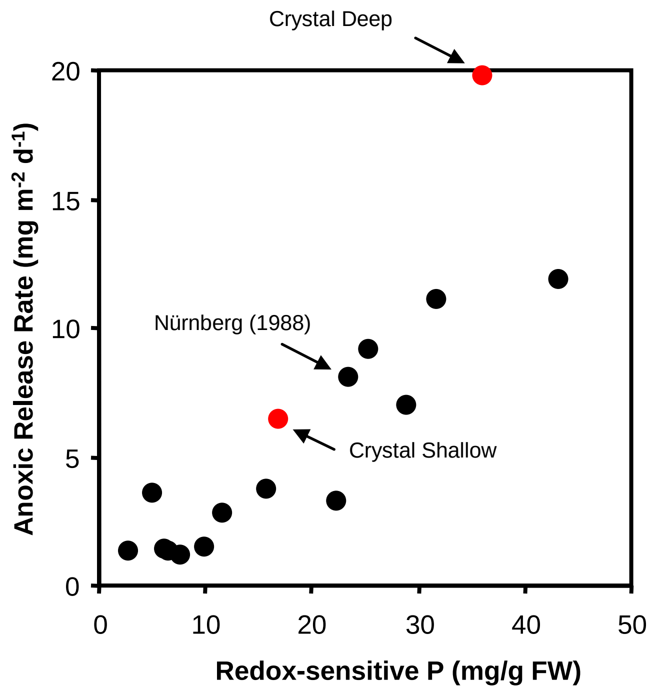
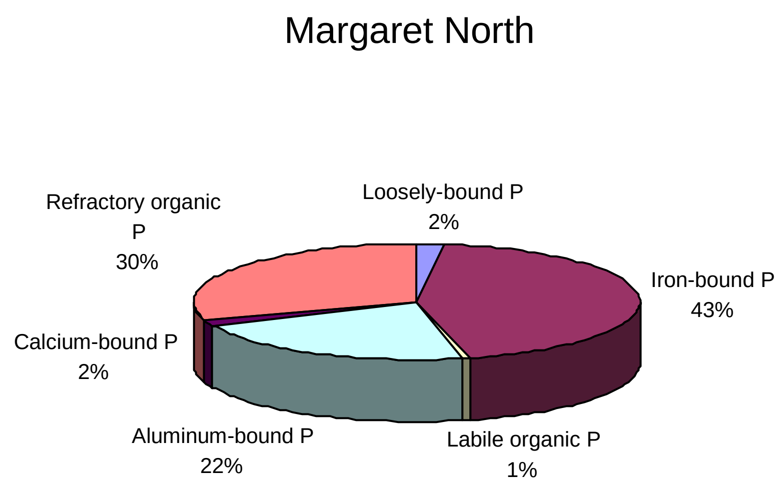


Figure 4. Redox-sensitive phosphorus (P) versus the anoxic release rate from Nürnburg (1988). Solid red circles represent results for Crystal Lake sediment.



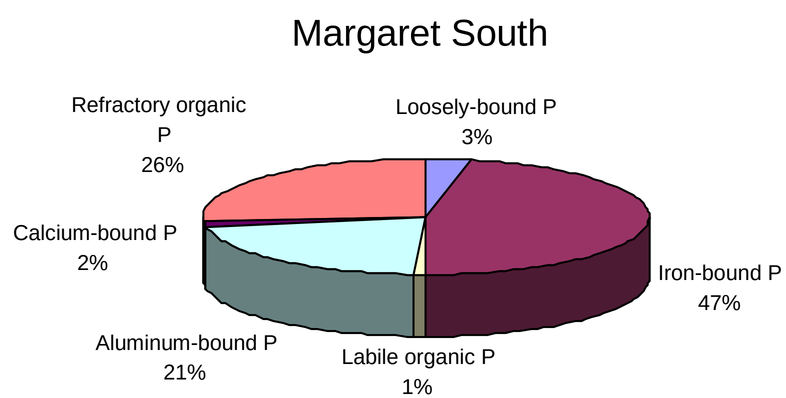


Figure 5. Sediment phosphorus (P) composition for Margaret Lake sediment.