Diagnostic Assessment of Lake Shirley from 2015-2017 Studies, with Management Implications

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Introduction

The Lake Shirley Improvement Corporation (LSIC) has been working to manage Lake Shirley for many years, and the lake has been subject to various studies over the last three decades. Limited water quality investigation has been conducted over the last 20 years, but there has been active management of rooted plants. More recent occurrence of cyanobacteria blooms prompted renewed interest in water quality. Water Resource Services (WRS) was retained by the LSIC initially to evaluate plankton and to review past water quality assessments in 2015, and then was further contracted to conduct additional investigations in 2016 and 2017 to aid understanding of conditions and development of a management plan. Investigative tasks have included:

- Phytoplankton and zooplankton analyses
- Storm water reconnaissance and sampling
- In-lake water quality assessment in spring and summer
- Sediment sampling and assessment
- Ground water seepage assessment
- Reconsideration of coupled watershed-lake models

Project Approach

WRS staff reviewed past studies and related data provided by the LSIC prior to 2015. WRS performed plankton analyses in 2015 and expanded the program to include in-lake water quality assessment in 2016 and 2017. Targeted studies on watershed inputs with a focus on storm water, sediment composition and possible internal loading of phosphorus, and ground water seepage as a source of nutrients, were conducted in 2016 and 2017. With a limited budget, the intention was to gather enough data to suggest management options relating to water quality and algae blooms. Rooted plant issues are addressed separately by SOLitude Lake Management (formerly Aquatic Control Technology), which has managed rooted plants in Lake Shirley for many years and prepared an updated plan in 2016.

Plankton analyses include phytoplankton and zooplankton, the former collected as whole water samples and the latter as net tows. Samples are preserved with glutaraldehyde, processed in the lab, and examined under microscope magnification of 100 to 400X. Quantitative counts of algae cells and zooplankton individuals with size measurements allows estimation of biomass per unit volume of lake water.

Profiles of temperature, oxygen, pH, conductivity, turbidity and chlorophyll-a by fluorescence were obtained with a Hach Hydrolab DS5 multi-probe field instrument at three lake stations (upper, middle, lower, Figure 1) on two dates in 2016 and three dates in 2017, with

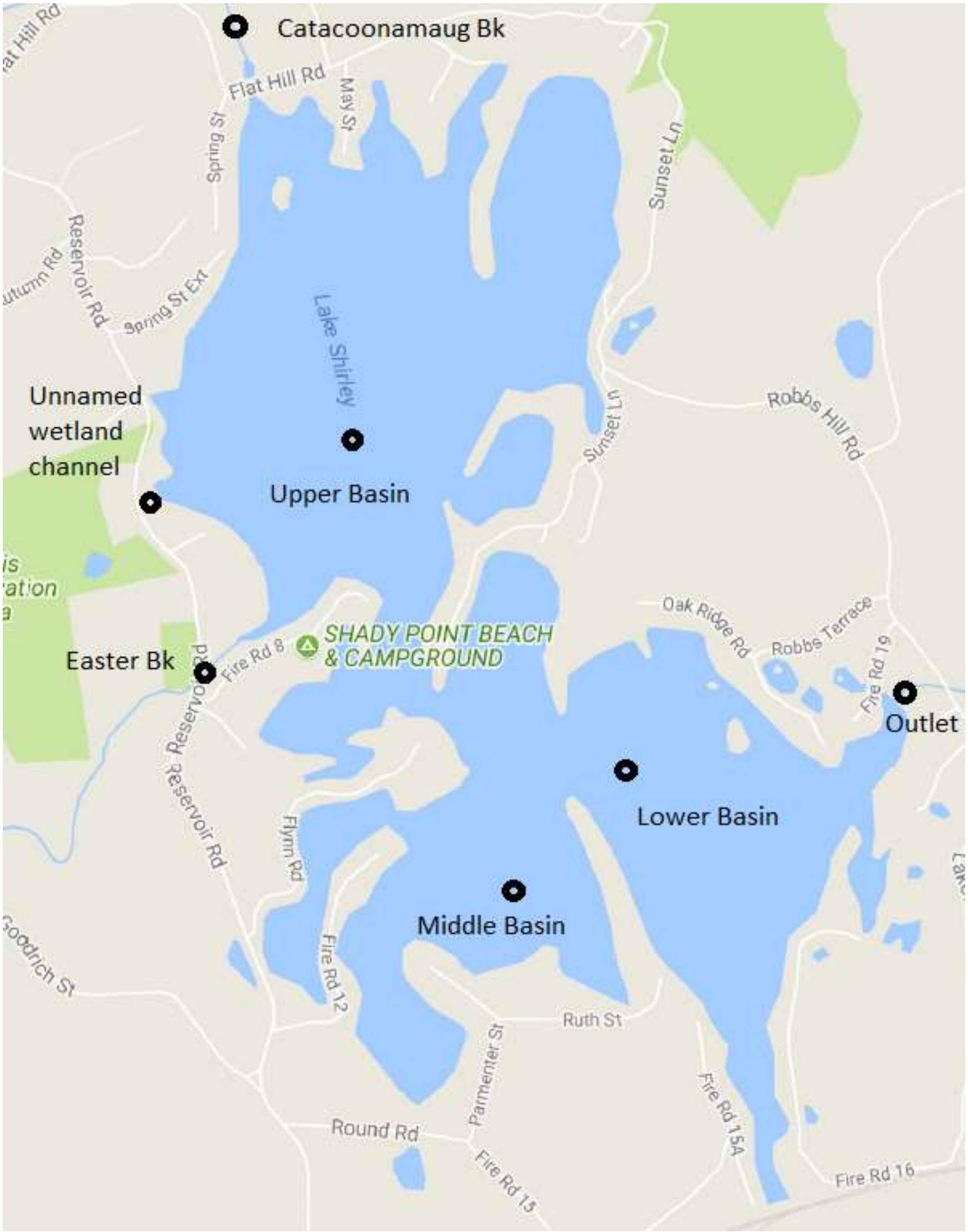


Figure 1. Surface water, storm water and sediment sampling stations at Lake Shirley

measurements at least every meter from surface to bottom. Water samples were collected from near the surface at the upper and middle lake stations, and from the surface and bottom of the lower lake station. Water samples were tested at Microbac Laboratories in Connecticut for forms of phosphorus and nitrogen by standard methods.

The quality of inflows was determined by sampling the two main tributaries, Easter Brook and Catacoonamaug Brook, plus an unnamed input from a wetland slightly north of Easter Brook (Figure 1). Samples were collected during dry conditions as grab samples, while first flush storm water samples were collected with passive devices mounted on rebar stakes placed in the stream channels such that containers were filled upon the initial rise in water level with rainfall. A post-storm sample was collected on the waning part of the hydrograph, after cessation of rainfall but before background flow conditions were reached. WRS set up the sampling system, but a team of LSIC volunteers collected most samples. Sampling was completed in 2016, but no sampling was performed in 2017, limiting the data base for this typically variable input source.

Surficial sediment was collected with an Ekman dredge at each of the three lake stations (Figure 1) and tested at Northeast Laboratories in Connecticut for percent solids, percent organic matter, iron-bound phosphorus, and total phosphorus.

Ground water seepage was assessed by placing seepage meters in nearshore areas (Figure 2), allowing them to incubate for 2-4 hours, and recording the change in water volume in attached bags. Multiplying volume by area by time, the seepage in liters per square meter per day was calculated. By assigning each seepage meter to an area extending half-way to the next seepage meter and out to the depth at which muck became more than a foot thick, the total seepage into the lake was estimated.

Results

Review of past studies

Studies by M&E in 1986 and BSC in 1999 provided most of the available water quality information prior to 2015. Lake Shirley is a 354 acre lake divided into 3 recognized basins (Figure 3). Two of the basins are shallow, with maximum depths of about 11 feet. The third and most downstream basin is not deep over most of its areas, but has a small area (11 acres) with maximum depth at 38 feet. The average depth of Lake Shirley is 7.2 feet and the total volume at full pool elevation is 2557 ac-ft. the flushing rate has been estimated at 4.07/yr, which equates to a detention time of 89 days.

Figure 2. Locations of Lake Shirley seepage measurements

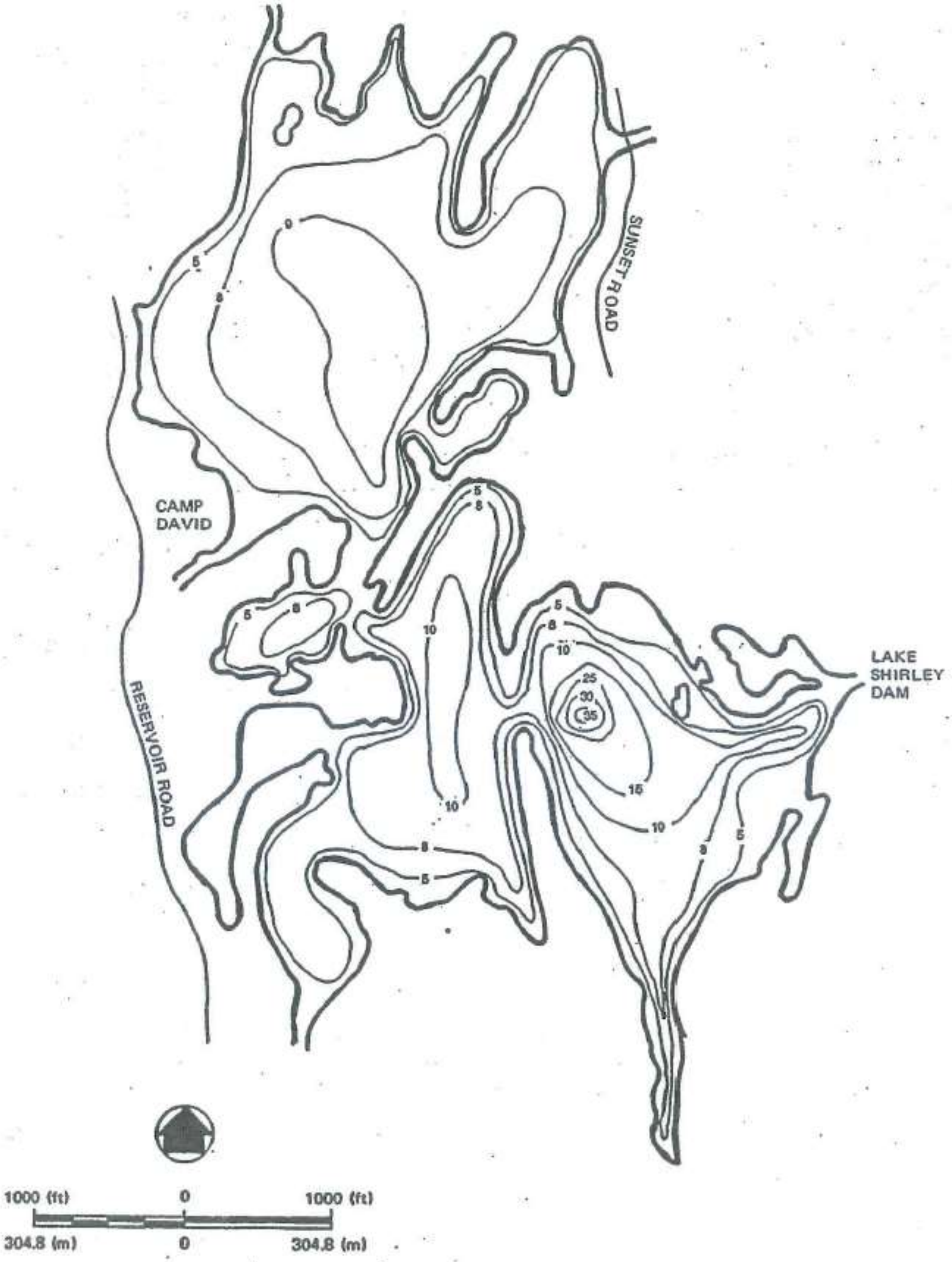


Figure 3. Bathymetry of Lake Shirley

The watershed covers 9050 acres, with 6 drainage areas identified but only two (Easter and Catacoonamaug) providing most of the drainage area and 70% of the total flow to Lake Shirley. The watershed is 52% forested, 12% cropland, and 8% residential (lots mostly >0.5 ac). A model applied by DEP model used 52% forest, 28% rural, 11% urban, and 219 septic systems <100 m from the lake. Sandy, porous soils seem to cover most of the watershed, but the area is glacially influenced and may have underlying clay and till soils.

The bottom of the lake is sandy to gravelly at the margin and mucky over most of the lake area. Past sediment testing revealed TP at 139-759 mg/kg and iron at about 20,000 mg/kg. It is likely that much P is bound to iron and could be released if oxygen levels are low at the sediment-water interface.

Surface water and septic P load was estimated at 519 kg/yr by M&E and 652 kg/yr by BSC. M&E also estimated 145 kg/yr from sediment, precipitation, and background ground water inseepage. It was estimated that 38% of the incoming P was retained in lake. The internal P load (release from sediment) was considered nominal (<2%) in 1986, but was estimated to be larger larger but not dominant in 1999. The nitrogen (N) load was estimated at 10,116 kg/yr, suggesting an N:P ratio of about 12.6 from loads. This is low enough to promote cyanobacteria that can use dissolved N gas, but not extremely low.

Tributary P concentrations tend to average 0.03 to 0.04 mg/L during dry weather, but values up to 0.11 mg/L have been observed. Wet weather tributary P values tend to be higher, up to 0.14 mg/L, but averaged about 0.07 with high variation over space and time, which is typical for storm water. Ammonium-N tends to be <0.3 mg/L in tributaries, but other N forms were less studied.

Catacoonamaug Brook was the largest contributor of P at about 279 kg/yr (43% of the estimated total load), but it drains 61% of the watershed, so the yield per unit area is lower than for other areas. Easter Brook contributes an estimated 126 kg/yr (21% of the total), while it drains just over 19% of the watershed. The direct drainage area to the lake, mostly the developed shoreline area, contributes about 162 kg/yr (25% of total P load) but covers only about 10% of the watershed, making it one of the largest contributors per unit area.

In-lake P concentration was 0.03 to 0.06 mg/L in the upper water layer, which is most of the lake and all of the upper and middle basins. P concentration averaged 0.13 mg/L in the deepest area in the lower basin. These concentrations are all large enough to support algae blooms. However, not all the total P is available, and with high organic content and sometimes low pH, P may still limit algae growth in Lake Shirley.

Oxygen is low near the sediment in water >8 feet deep, but did not appear devoid of oxygen in past measurements except in the “deep hole” of the lower basin. Water clarity has been <4 ft in many summers, a low value that used to be grounds for closing beaches for public safety, but is just a warning threshold now. The 1999 BSC study indicated a decline in lake condition since the 1986 M&E study.

Rooted plants were surveyed by Geosyntec in 2006 and SOLitude or its predecessor ACT in most years since then. Rooted plant growth can be dense, given that so much of the lake is shallow and the substrate is largely a mix of sand and organic muck, optimal for plant growth. Fanwort (*Cabomba caroliniana*), Eurasian watermilfoil (*Myriophyllum spicatum*) and variable watermilfoil (*Myriphyllum heterophyllum*) have invaded Lake Shirley and have caused use impairment. Spiny naiad (*Najas minor*) is another invasive species noted from the lake, but is less of an impairment threat. Curly leaf pondweed (*Potamogeton crispus*) is a more recent invasive species in the lake, but usually dies back by early summer and is less of a concern.

Native species of rooted plants in Lake Shirley include 23 species, with coontail (*Ceratophyllum demersum*), Robbins’ pondweed (*Potamogeton robbinsii*), and water celery (*Valisneria americana*) most abundant. Sometimes water lilies (yellow and white) are abundant in peripheral patches, but are not found far from shore.

Problems with rooted plant have generally been addressed with herbicides and drawdown. Dredging has been recommended in the past as a superior control technique, but the cost was prohibitive. It was estimated by BSC in 1999 that 800,000 cubic yards of material would have to be removed at a cost in excess of $10 million, and that cost would be considered very low today.

From pre-2000 studies, water quality had declined but cyanobacteria were not a big problem. This has changed, however, and cyanoblooms have been an intermittent summer problem over the last decade. Increasing problems with cyanobacteria have caused the lake to be posted with warnings against contact recreation in parts of recent summers. Cyanobacteria have multiple bloom modes, and it is possible that growths start at the sediment-water interface and rise to form a bloom after accumulating sufficient nutrients. It is also possible that they are reacting to storm inputs. There does appear to be a progression of conditions from north to south, from the upper basin to the lower basin, with the worst conditions in the north/upper basin. Conditions are not necessarily acceptable in the other basins, but blooms may be worse in the upstream portion of the lake where the two major tributaries enter.

In-lake Water Quality

Temperature was fairly uniform top to bottom except in the one deep area in the lower basin (Figure 4). Temperatures increase from spring through summer, consistent with seasonal expectations, but after May the temperature exceeded 20^{o}C in all three basins, indicating poor conditions for coldwater fish. The deep area of the lower basin maintains a colder temperature, but has minimal oxygen in those deep waters. We would not expect to find trout in Lake Shirley, but warmwater fish such as sunfish, bass and pickerel would do fine.

Oxygen tends to be >5 mg/L in all areas <3 m (10 feet) deep (Figures 5-7), which is the vast majority of the lake. However, profiles from the one deeper area in the lower basin indicate a sharp loss of oxygen in water >3 m deep. Slight thermal stratification is enough to limit mixing and allow oxygen demand from bottom sediment to cause oxygen depletion near the sediment-water interface, however, and while overlying water had adequate oxygen, insertion of the DO probe into the sediment yielded low oxygen in water >2.7 m (9 ft) deep. This suggests that undesirable sediment-water interactions associated with low oxygen may occur over a large area in Lake Shirley.

Conductivity (Figure 8), which represents dissolved solids but does not indicate the composition of those solids, is fairly stable over space and time at a moderate level between 240 and 305 µmhos/cm. There is a slight increase with depth and over the summer, both likely related to release of dissolved substances from the sediment under low oxygen conditions. Background conductivity in this area is around 100 µmhos/cm, so the observed values, while moderate, are elevated from natural levels for this area.

The pH (Figure 9) ranged from 6.6 to 7.6 SU near the surface, slightly higher than might be expected for this relatively acidic landscape, but likely an effect of photosynthesis by abundant rooted plants and algae. The pH declined with depth, indicating less photosynthesis (which removes CO2 and raises pH) and more release of acids from decomposition (largely in the sediment).

Alkalinity (Figure 10) was measured by field titration and is not part of the instrument bearing probes for other field water quality. Values were between 18 and 36 mg/L except in the deep section of the lower basin on the last day of sampling (Sept 2017, with a value of 65 mg/L), a low to moderate level typical of this area. The higher values for deep water reflect releases of substances from the sediment.

Turbidity (Figure 11), which is a measure of light attenuation and represents suspended solids in the water column, was between 3 and 8 NTU for most stations and depths, a moderate to slightly

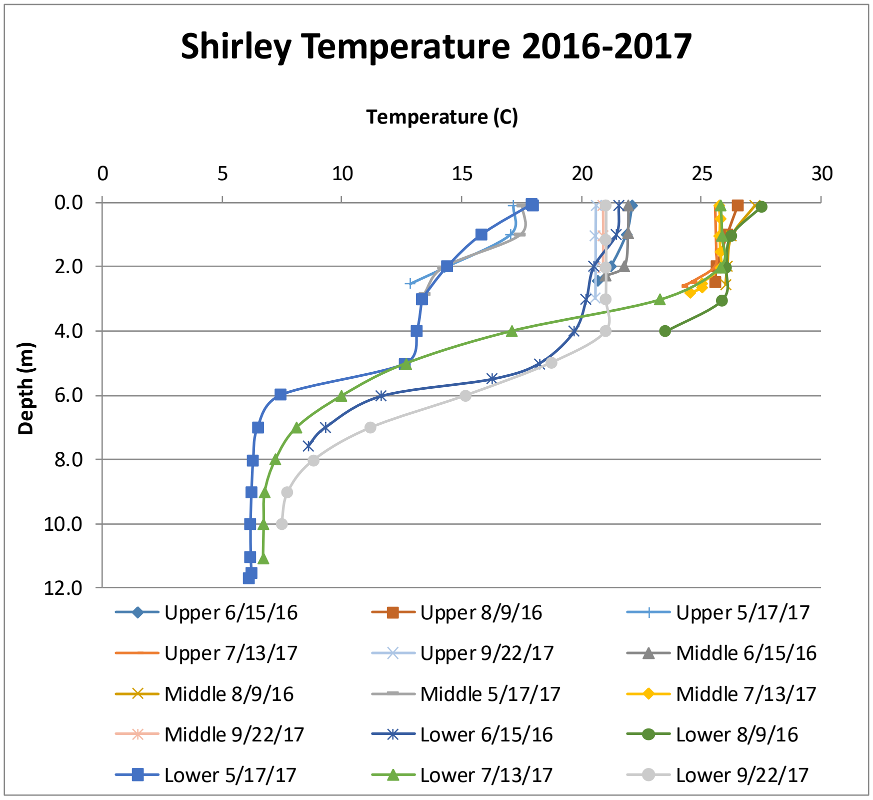


Figure 4. Temperature in Lake Shirley in 2016-2017

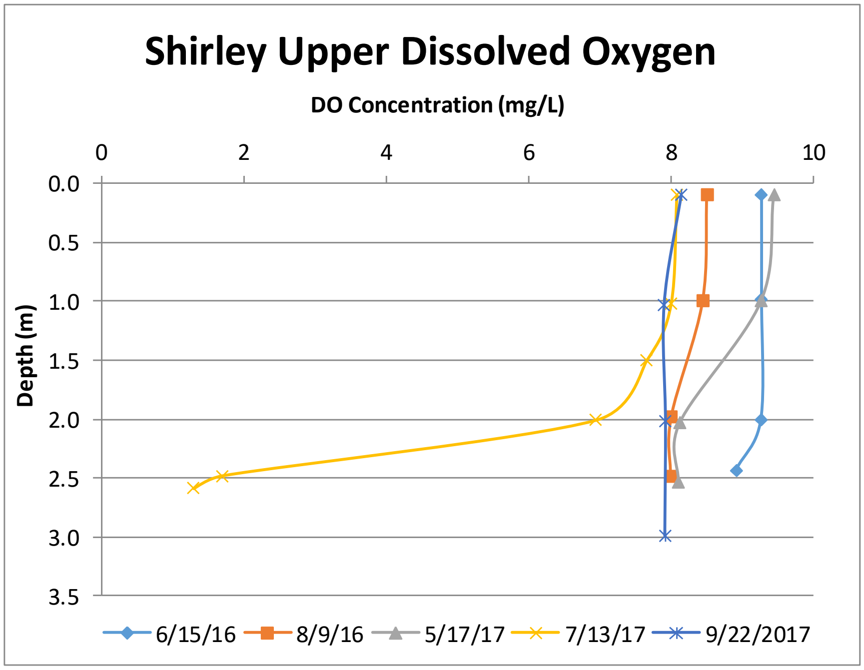


Figure 5. Dissolved oxygen in the upper basin 2016-2017

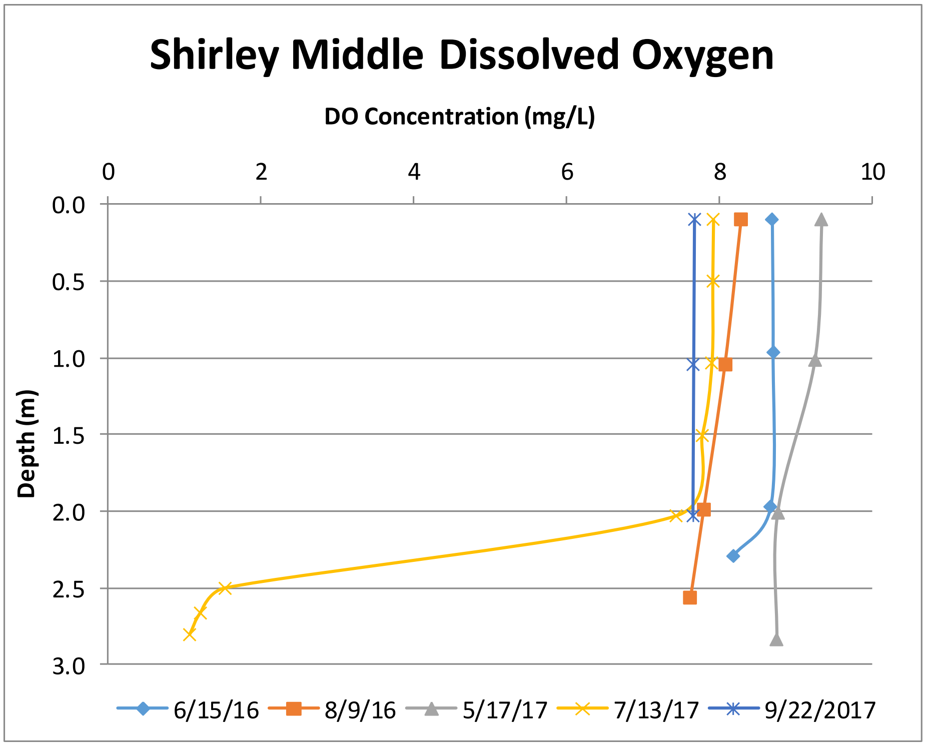


Figure 6. Dissolved oxygen in the middle basin 2016-2017

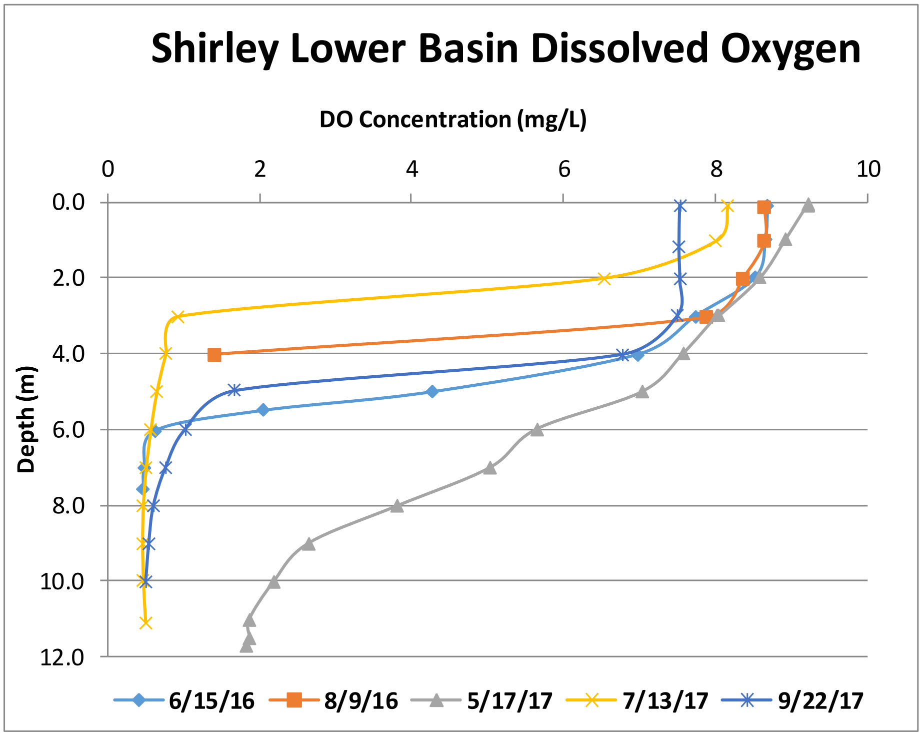


Figure 7. Dissolved oxygen in the lower basin 2016-2017

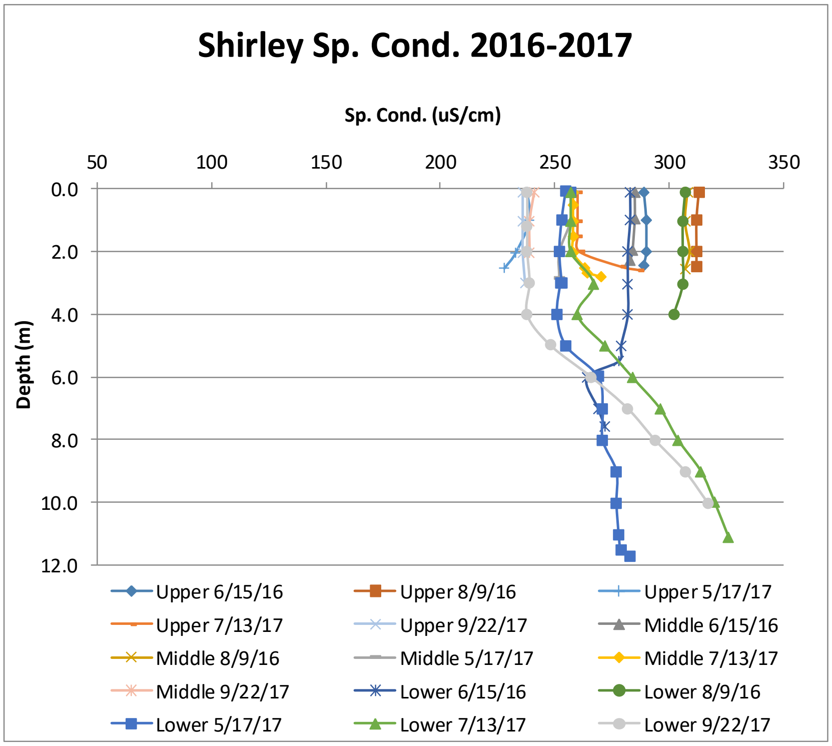


Figure 8. Specific conductivity in Lake Shirley in 2016-2017

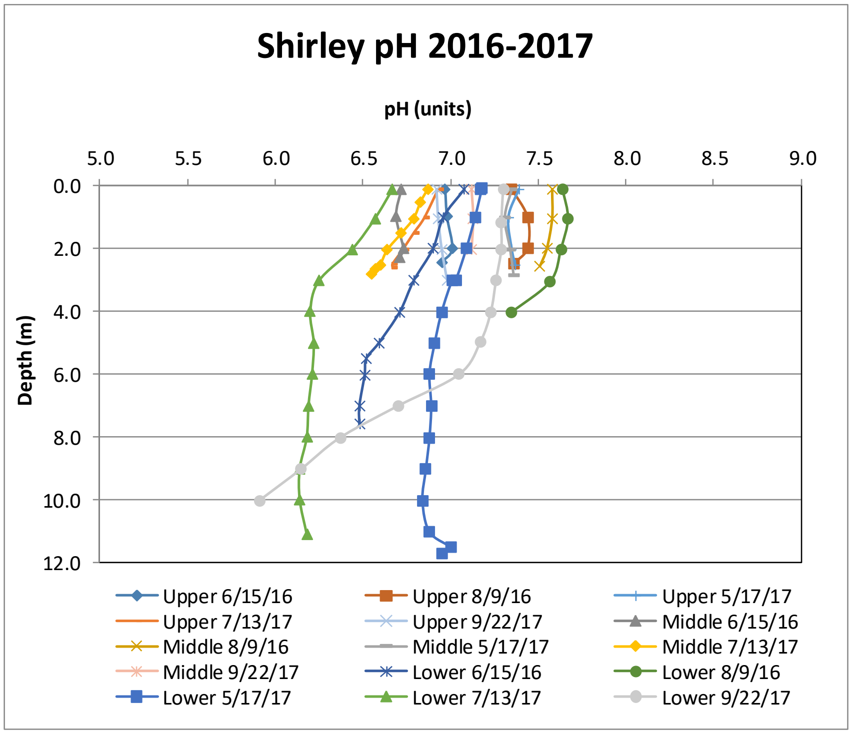


Figure 9. pH in Lake Shirley in 2016-2017

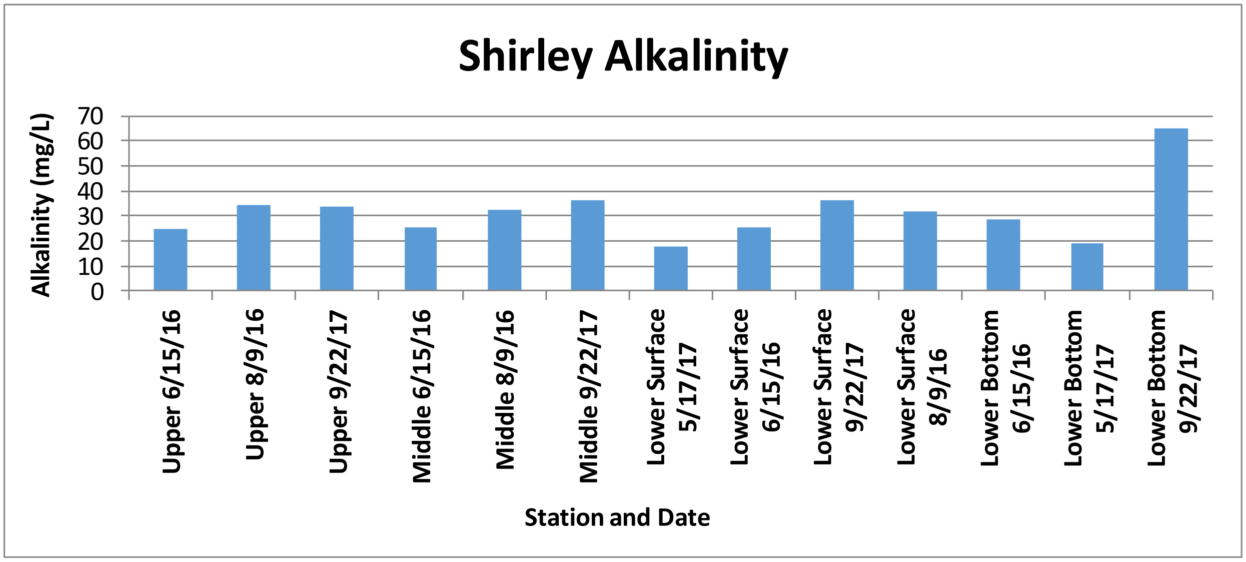


Figure 10. Alkalinity in Lake Shirley in 2016-2017

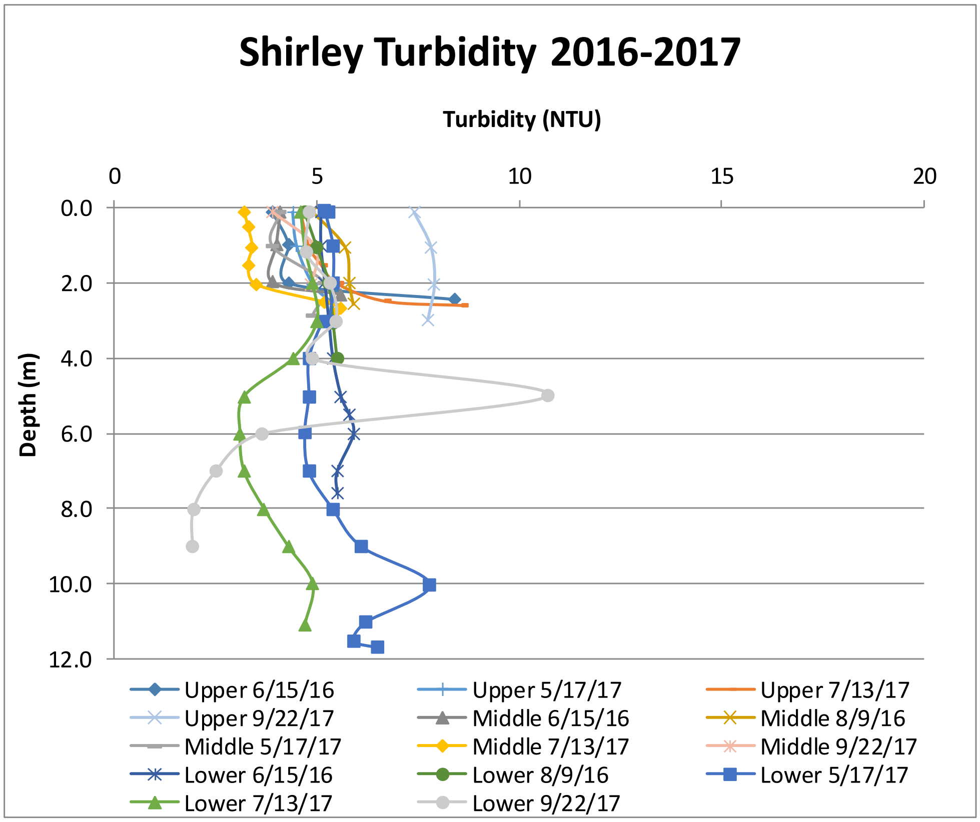


Figure 11. Turbidity in Lake Shirley in 2016-2017

elevated range. Algae can cause high turbidity, but much of the elevated turbidity appears to be a function of suspended non-living organic particles. Average chlorophyll-a values from field fluorescence (Figure 12) in Lake Shirley were higher than 4 µg/L, the general threshold for low algae biomass, in 12 of 15 samples, but exceeded 10 µg/L, the threshold for high biomass, in only 2 samples, both in the upper basin. These values are high enough to impart color to the water, but are not high enough to explain the high turbidity in at least the upper basin. A mix of algae and resuspended organic sediment is likely involved in turbidity levels in Lake Shirley.

Water clarity, as assessed by Secchi transparency (Figure 13), were rarely higher than 3 m and sometimes lower than 2 m. Secchi readings collected by volunteers were similar on dates closest to the WRS sampling, and additional data from volunteer monitoring helps characterize the pattern in Lake Shirley over space and time. Clarity tends to increase from north to south, inlets to outlet, upper to lower basin. Clarity tends to decrease from spring through summer, although weather patterns can affect this trend. But overall clarity is not high, and the range is not wide. No major algae blooms were observed in 2016 and 2017 (copper was used to prevent a bloom in 2017), which kept clarity from declining even more. Algae affect clarity, but so does suspended sediment, and WRS staff noted substantial boat-induced sediment suspension during site visits. A combination of factors led to observed low clarity, all of which tend to cause decreased clarity over the course of the summer.

Nitrogen levels in Lake Shirley (Figure 14) include ammonia, nitrate (the analysis for which includes nitrite, but nitrite is minimal in lakes) and organic nitrogen, adding up to total N. N was not fractionated in all samples due to preservation requirements if samples cannot be delivered to the lab the same day, but that fractionation is provided for samples on which is was performed. Values for total nitrogen (TN) in excess of 0.5 mg/L are moderate, while values >1.0 mg/L are considered high; only 6 of 15 TN values were >0.5 mg/L for shallow water samples, but all but one value from the deep bottom station in the lower basin exceeded 1.0 mg/L. That station is subject to low oxygen and accumulation of ammonia and organic N. Nitrates are not a dominant component in any sample; nitrates are a preferred N source for algae and the low values may indicate N limitation of production. Under such conditions, certain blue-green algae that can utilize N gas dissolved in the water column are favored.

Phosphorus levels in Lake Shirley (Figure 15) range from 0.010 to 0.033 mg/L for surface samples, with values of 0.028 and 0.390 mg/L for the deep sample in the lower basin. The 8/9/16 bottom sample from the lower basin was collected at only 4 m; the value likely would have been much higher if collected near the bottom in 6+ m (20 ft) of water. Values >0.010 mg/L represent a risk of algae blooms, although we usually set the likely problem level at 0.20 mg/L. While all samples had TP of at least 0.010 mg/L, only 6 of 15 surface samples exceeded 0.020 mg/L, so

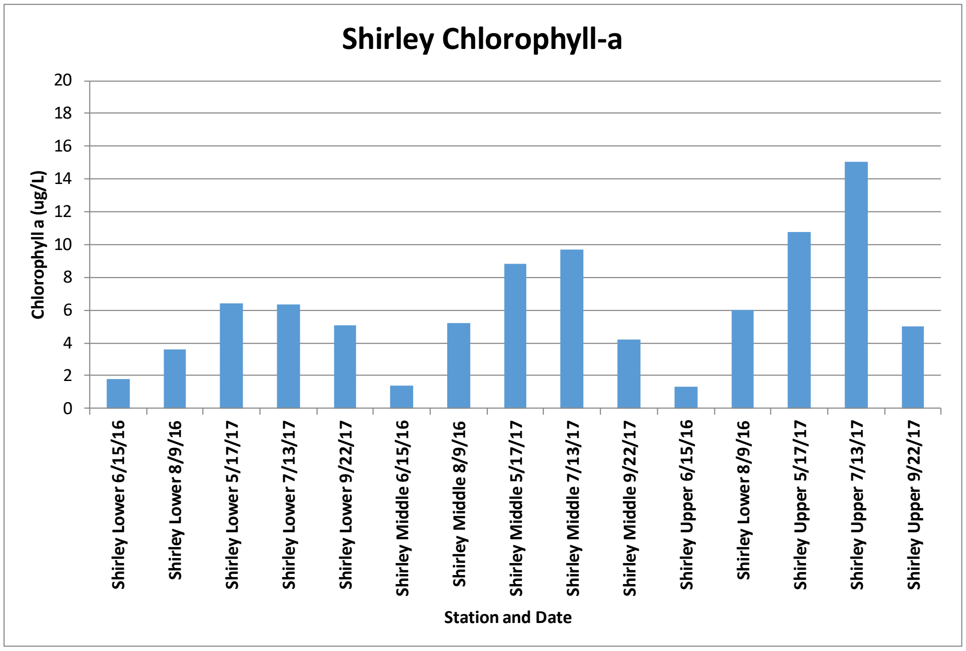


Figure 12. Chlorophyll-a in Lake Shirley in 2016-2017

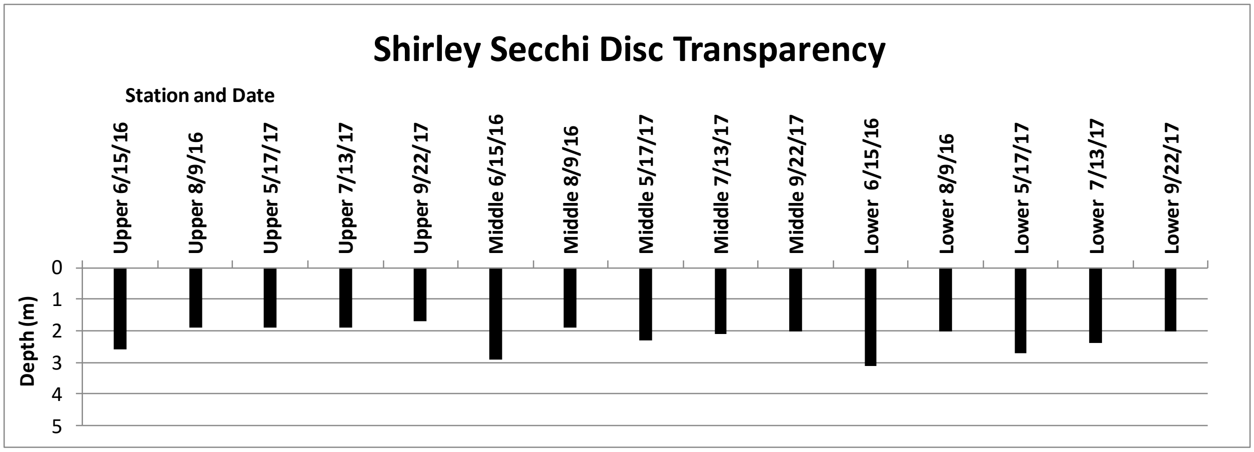


Figure 13. Secchi disc transparency in Lake Shirley in 2016-2017

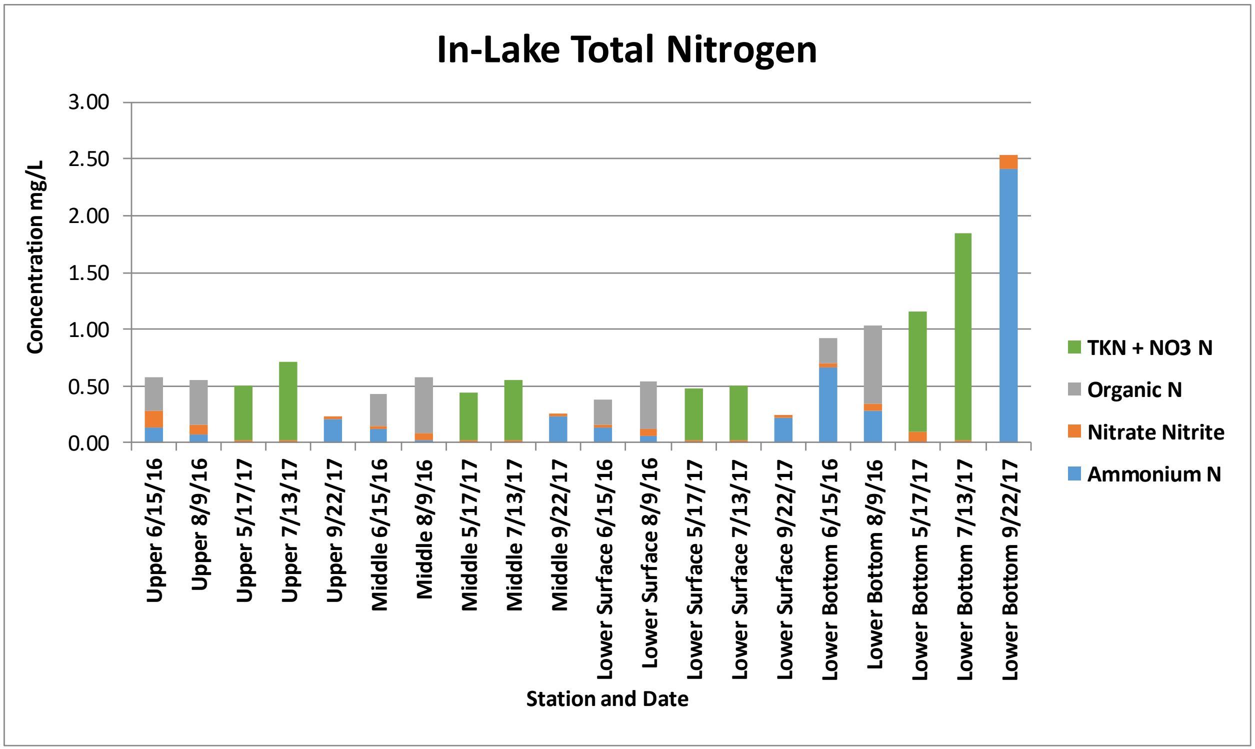


Figure 14. In-lake total nitrogen in Lake Shirley in 2016-2017

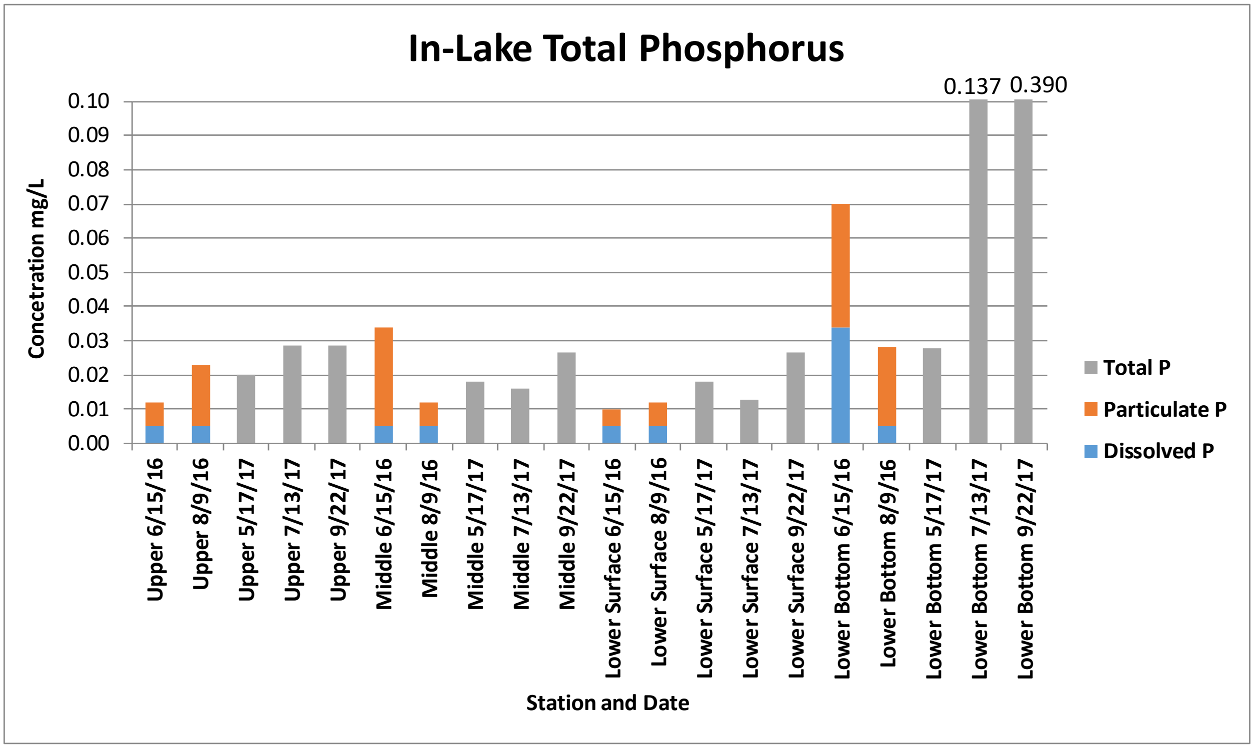


Figure 15. In-lake total phosphorus in Lake Shirley in 2016-2017

while P is not low, it is also not routinely excessive. Where measured, dissolved P was low in all but the deep samples, where release from sediment under low oxygen levels fosters such accumulation. Surface water TP was higher in the upper basin than in the middle or lower basins, consistent with past observations.

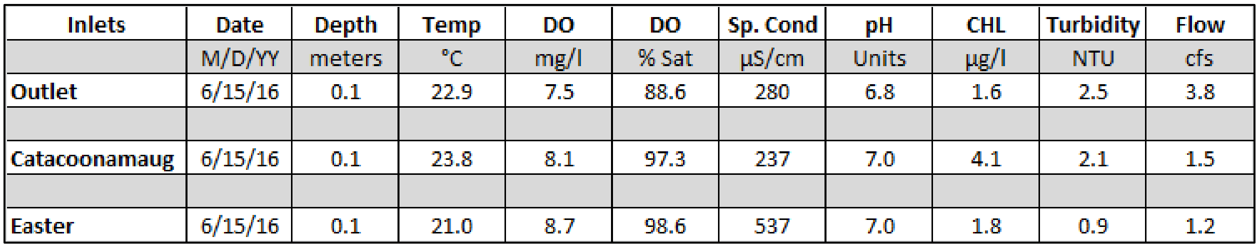
Storm water reconnaissance and sampling

Surface water inputs in general and storm water runoff in particular are often very influential in determining lake conditions. We toured the watershed and lake shoreline to assess key input points for surface water and understand the drainage pattern. While there are steep slopes in many areas, erosion was limited and storm water drainage systems were few. The main surface water inlets are all to the upper basin of the lake. Drainage from shorefront properties goes direct to the lake, but with few pipes or ditches that were evident. Drainage within the apparent watershed but off the lake goes mostly to wetland or ponded depressions. These may overflow to the lake in especially wet periods, but provide substantial detention and no overflow was observed on any site visit in 2016 or 2017. Much of this water may move more slowly through the sandy soil to the lake, removing many possible contaminants.

Lake Shirley inlets include Easter Brook, Catacoonamaug Brook, and a wetland tributary off of Reservoir Road. These were sampled in dry weather, during first flush and post storm conditions, although not all sampling was complete for any storm and samples were only collected in 2016. Sampling was conducted with the aid of Les Smith. Passive samplers were placed in the streams to capture first flush storm water, while grab samples were collected before and after storms when possible. Samples were tested for ammonia (AN), total kjeldahl nitrogen (TKN), nitrate+nitrite (NN), total phosphorus (TP) and dissolved phosphorus (DP) if delivery was possible the same day as collection. If preserved for later delivery, only TP, TKN and NN could be tested. Summer of 2016 had few rain events. In comparison to the last 8 years, there was a little less than half (48%) the average precipitation from May to August. Despite this we were able to capture at least partial data from 4 storm events, with Easter Brook successfully sampled most frequently.

On June 15, 2016, the two main inlets to Lake Shirley and the outlet were assessed under dry weather conditions for water quality parameters measured by field instruments, including temperature, dissolved oxygen, specific conductivity, pH, chlorophyll a, and turbidity (Table 1). Note that the sum of the two main inflows does not add up to the measured outflow, suggesting other water sources, especially with some evaporation in between inflow and outflow. No other flowing surface water was observed on that date, and the difference could have been supplied by ground water inseepage, but the water level in the lake could also have been changing, so the mismatch is not striking or easily explained. The only issue suggested by dry weather field data was the elevated conductivity in Easter Brook; all other values were within the expected range.

Table 1. Field water quality data under dry conditions



Inlets	Date	Depth	Temp	DO	DO	Sp. Cond	pH	CHL	Turbidity	Flow
	M/D/YY	meters	°C	mg/l	% Sat	µS/cm	Units	µg/l	NTU	cfs
Outlet	6/15/16	0.1	22.9	7.5	88.6	280	6.8	1.6	2.5	3.8
Catacoonamaug	6/15/16	0.1	23.8	8.1	97.3	237	7.0	4.1	2.1	1.5
Easter	6/15/16	0.1	21.0	8.7	98.6	537	7.0	1.8	0.9	1.2

Field data are not collected by passive samplers, and the focus of that effort is on laboratory data for nutrients (Table 2, Figure 16). In general, most values are moderate, with a few higher and lower values, but no clear trend of excessive nutrient levels was detected. It is expected that forms of N and P will be elevated in first flush storm water, but the expected runoff P concentration for developed areas is >0.30 mg/L and the expected N level is >3 mg/L. Very few values exceeded these thresholds. The area is not extensively developed, and there are many wetlands that help trap nutrients. Most N and P enter the lake as particulate matter which is not readily available for algae or plant use and becomes part of the sediment by settling, as evidenced by the fractionation of P and N forms for Easter Brook (Figure 17).

There is considerable variation in nutrient levels over time and space, and it normally requires 10 or more storms spread out over several years to adequately characterize storm water. More storm water sampling will therefore be needed, and it is unfortunate that samples were not collected in 2017. Yet the results suggest a fairly normal pattern of low inputs during dry weather, a short period of elevated inputs early in a storm, then a return to lower loading as accumulated contaminants are washed out of the drainage area. The peak inputs may indeed represent substantial loading, but this occurs only during a relatively small period of time overall.

Considering potential impact of inputs on a lake, we tend to flag values >0.05 mg/L for TP and >1.0 mg/L for TN. All three sampled inlets exhibited high values in at least one event (Figure 16) by those thresholds, but high values do not occur all the time. Looking at Easter Brook, which yielded the most samples, TP and TN were elevated in 2 of 4 first flush samples and 2 of 6 samples overall. There is certainly a storm water issue to be addressed, but incoming water quality is not a daily threat to the health of the lake.

Table 2. Water quality data from tributaries

Parameters	Pre Storm			1st Flush			Post Storm			1st Flush			1st Flush			1st Flush		
Date	6/15/16		6/27/16	6/28/16			6/28/16			7/16/16			8/13/16			8/14/16		
	Easter Dry 6/15/16	Cata. Dry 6/15/16	Res Rd wetland pre-storm 6/15/16	Easter 1st flush 6/28/16		Res Rd wetland 1st flush 6/28/16	Easter post-storm 6/28/16	Cata. post-storm 6/28/16	Res Rd wetland post-storm 6/28/16	Easter 1st flush 7/16/16	Cata. 1st flush 7/16/16		Easter 1st flush 8/13/16			Easter 1st flush 8/14/16	Cata. 1st flush 8/14/16	
Ammonium N (mg/L)	0.120	0.190	0.072	0.025			0.025	0.120	0.052				0.130			0.670	0.240	
Nitrate N (mg/L) NOX	0.410	0.025	0.025	0.460		0.099	0.460	0.072	0.025	0.590	0.056		0.470			0.095	0.068	
TKN (mg/L)	0.420	0.600	0.360	0.260		2.100	0.300	0.650	0.500	0.240	0.480		0.900			6.900	3.000	
Org N (mg/L)	0.300	0.410	0.288	0.235			0.275	0.530	0.448				0.770			6.230	2.760	
Total Nitrogen (mg/L)	0.830	0.625	0.385	0.720		2.199	0.760	0.722	0.525	0.830	0.536		1.370			6.995	3.068	
Total Phosphorus (mg/L)	0.014	0.041	0.015	0.010		0.220	0.014	0.056	0.029	0.026	0.050		0.099			0.079	0.260	
Dissolved Phosphorus (mg/L)	0.012	0.026	0.030	0.005			0.005	0.028	0.005				0.030			0.005	0.014	
Particulate P	0.002	0.015	-0.015	0.005		0.220	0.009	0.028	0.024	0.026	0.050		0.069			0.074	0.246	

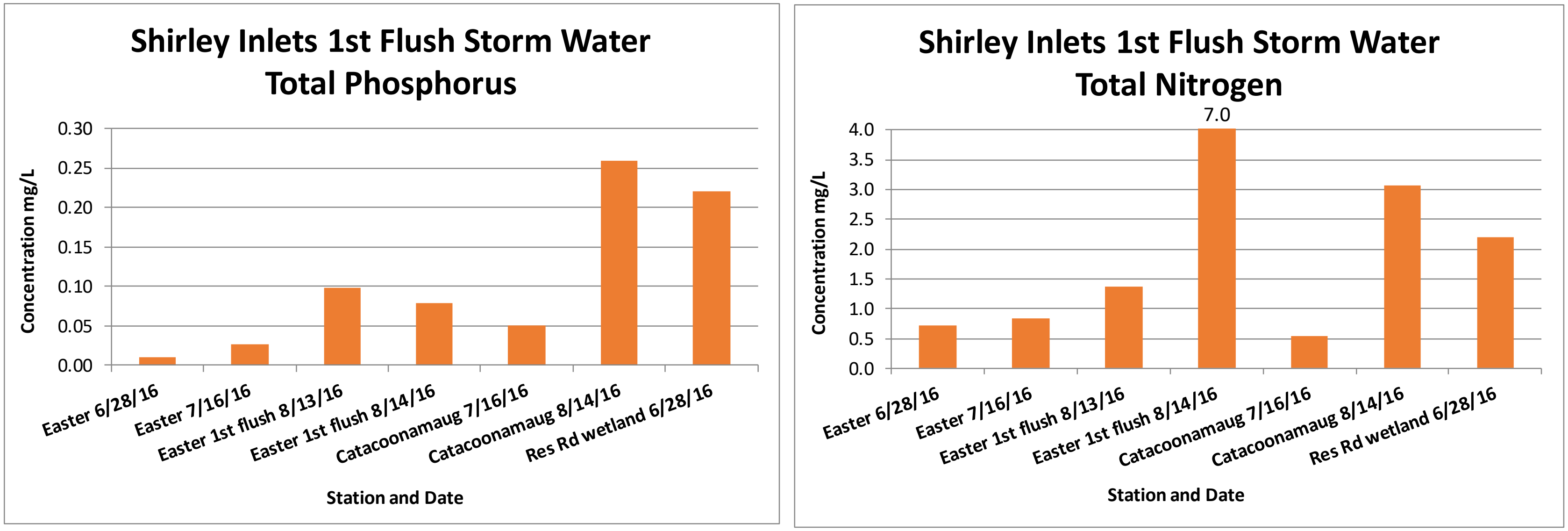


Figure 16. First flush storm water total phosphorus and total nitrogen

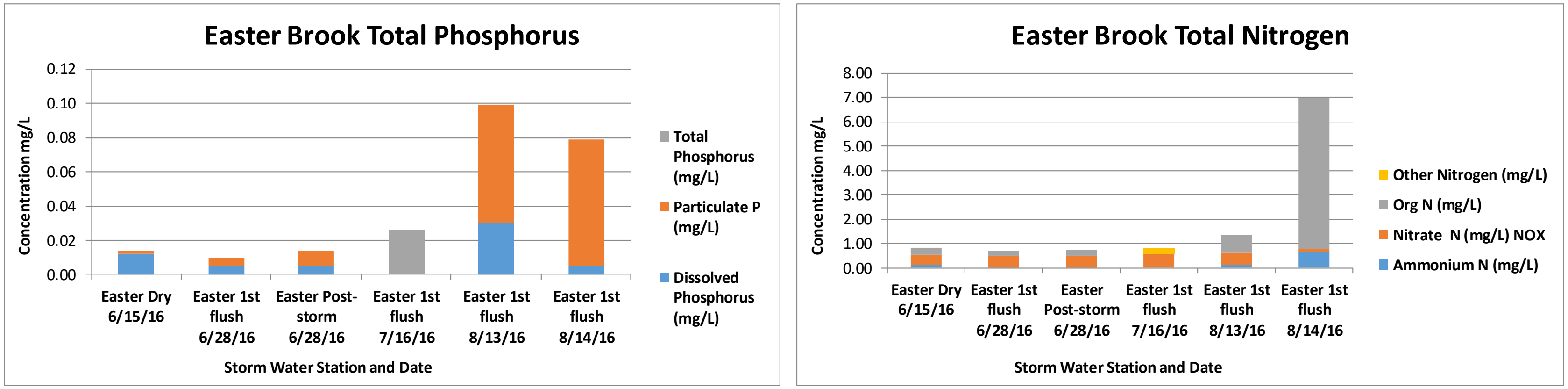


Figure 17. Fractionation of total phosphorus and total nitrogen in Easter Brook samples

Seepage

Measurement of the amount of water seeping into Lake Shirley as ground water was conducted in June 2017. Many more measurements over multiple periods of time could improve the estimate, but this was the first effort we know of to quantify inseepage quantity and quality for Lake Shirley. Given that ground water appeared to be a potentially large contributor of N and P, this effort was considered essential. Seepage of <5 L/m^2/day are considered low, while values >20 L/m^2/day are considered high. The seepage quantity varied from 0.6 to 6.0 L/m^2/day (Table 3), a low range that was surprising for what appeared to be sandy soils. The ground water table may be low relative to the normal lake level, which is raised by a dam over the natural elevation. The thick organic muck also impedes ground water exchange, and there may be substantial clay under the sand in the vicinity of the lake that also restricts ground water flow.

Samples collected at each seepage site with littoral interstitial porewater samplers provided values for dissolved P (tested as total P on filtered samples) and total dissolved N (tested as TKN and nitrate N in filtered samples) in the incoming ground water (Table 4). Dissolved iron was also assessed, as iron levels are often elevated in ground water and will inactivate P when the ground water is exposed to oxygen upon entry to the lake. P concentrations were generally low; only one value exceeded 0.05 mg/L, and not by much. TKN was also generally low, with only one value >0.5 mg/L, from the same sample that yielded the high P concentration. Nitrate was not high on average, but 4 out of 16 samples had elevated nitrate N (>2 mg/L), which is almost certainly a function of on-site wastewater discharges.

Multiplying the seepage quantity values by the corresponding areas they represent, the total inseepage in each shoreline segment was estimated (Table 5). The total ground water input was estimated at just over 1 million m^3 per year. Precipitation landing directly on the lake accounts for about 1.6 million m^3/yr, so while the ground water input is not negligible, it is not particularly large in comparison with other water inputs.

Multiplying the seepage quantity for each segment by the corresponding P and N concentrations, the load of each nutrient can be estimated (Table 5). The total input of P from ground water is estimated at 20.5 kg/yr, which is a minor portion of the total P load as calculated in past efforts. The total input of N from ground water was considerably higher, however, at 1360 kg/yr, which is probably a significant fraction of the total load of N to Lake Shirley. N is not removed by passage through soil, so N added to the ground water by on-site wastewater disposal systems can be expected to reach the lake. P is removed by soil rather readily, so it is not surprising that little of it makes it to the lake. Again, additional assessment may be warranted, but this initial effort does not suggest that ground water in general and on-site wastewater disposal in particular is a major source of P to Lake Shirley, but it may be a substantial source of N.

Table 3. Seepage measurements in Lake Shirley

Lake Seepage Dates: 6/14/17, 6/15/17, 6/19/17						
Station	GPS#	Water Depth (ft)	Distance From Shore (ft)	Total Time In Lake (hr)	Net Gain Volume mL	Seepage (L/sq.m/ day)
1	185	2.0	20.0	3.6	105	2.80
2	186	3.0	10.0	3.9	25	0.62
3	187	2.5	13.0	4.2	130	3.00
4	188	3.0	12.0	4.0	105	2.52
5	196	2.5	6.0	2.1	50	2.31
6	197	3.0	10.0	2.0	115	5.52
7	191	3.0	8.0	3.7	170	4.40
8	203	2.0	3.0	1.7	60	3.47
9	204	3.0	7.0	2.6	50	1.86
10	199	2.0	8.0	2.9	175	5.83
11	200	2.0	5.0	3.0	145	4.64
12	205	3.0	7.0	3.33	125	3.60
13	206	3.0	8.0	3.41	105	2.96
14	208	3.0	8.0	3.38	105	2.98
15	207	3.0	2.5	3.5	205	5.62
16	209	2.5	10.0	2.41	150	5.98

Table 4. Seepage water quality in Lake Shirley

Lake Shirley Ground Water_ June 2017				
Station	Total Kjeldahl Nitrogen	Total Phosphorus	Nitrate-Nitrite as N	Iron
	mg/L	mg/L	mg/L	mg/L
1	0.78	0.067	0.03	5.30
2	0.14	0.021	0.03	1.54
3	0.05	0.012	0.12	0.06
4	0.38	0.028	0.50	0.08
5	0.31	0.005	2.13	0.03
6	0.22	0.030	0.05	0.09
7	0.10	0.005	2.56	0.03
8	0.11	0.005	0.23	0.03
9	0.11	0.020	0.76	0.03
10	0.35	0.012	0.03	0.07
11	0.48	0.046	0.03	0.88
12	0.20	0.014	0.03	0.05
13	0.43	0.031	3.34	0.06
14	0.01	0.005	0.08	0.03
15	0.22	0.005	0.58	0.03
16	0.20	0.013	5.82	0.03

Table 5. Seepage water, phosphorus and nitrogen loads to Lake Shirley

		TKN	NO3-N	TDN	TDP	Area	Seepage quantity	Annual seepage	TDP	TDP	TDN	TDN
Station	GPS#	mg/L	mg/L	mg/L	mg/L	m2	L/m2/day	m3/yr	mg/day	kg/yr	mg/day	kg/yr
1	185	0.780	0.025	0.805	0.067	43,678	2.80	44639	8182	3.0	98451	35.9
2	186	0.143	0.025	0.168	0.021	40,934	0.62	9242	539	0.2	4254	1.6
3	187	0.050	0.115	0.165	0.012	38,844	3.00	42535	1363	0.5	19228	7.0
4	188	0.381	0.501	0.882	0.028	48,725	2.52	44817	3389	1.2	108297	39.5
5	196	0.310	2.130	2.440	0.005	46,314	2.31	39010	566	0.2	260781	95.2
6	197	0.223	0.051	0.274	0.030	71,314	5.52	143683	11731	4.3	107979	39.4
7	191	0.100	2.560	2.660	0.005	60,624	4.40	97338	1413	0.5	709364	258.9
8	203	0.108	0.227	0.335	0.005	72,047	3.47	91248	1325	0.5	83748	30.6
9	204	0.113	0.758	0.871	0.020	76,350	1.86	51847	2869	1.0	123723	45.2
10	199	0.348	0.025	0.373	0.012	61,445	5.83	130751	4191	1.5	133617	48.8
11	200	0.479	0.025	0.504	0.046	45,817	4.64	77596	9715	3.5	107147	39.1
12	205	0.196	0.025	0.221	0.014	52,633	3.60	69228	2617	1.0	41916	15.3
13	206	0.425	3.340	3.765	0.031	51,171	2.96	55210	4659	1.7	569500	207.9
14	208	0.109	0.077	0.186	0.005	20,297	2.98	22094	321	0.1	11241	4.1
15	207	0.218	0.583	0.801	0.005	17,206	5.62	35312	513	0.2	77493	28.3
16	209	0.200	5.820	6.020	0.013	35,299	5.98	76984	2700	1.0	1269709	463.4
TOTAL						**782,697**		**1031535**		**20.5**		**1360.2**

Sediment

Because oxygen can be low in water as shallow as about 9 ft and phosphorus bound to iron can become available to algae under low oxygen conditions, sediment in each basin was tested to determine the potential for “internal loading” of P to be a major P source (Table 6). The upper few inches of sediment can interact with the overlying water and were tested. For Lake Shirley, those sediments have low solids content (mostly water) and high organic content (34 to 63%), typical of lake muck that has accumulated over many years of plant and algae production. Total P levels in sediment are moderate, ranging from 255 to 835 mg/kg. Iron bound P, or Fe-P, is also moderate at 151 to 551 mg/kg. The middle basin had the lowest P concentrations, consistent with lower organic content, but the cause of the lower organic content is unknown. More sampling would be recommended before drawing definitive conclusions for this lake, but there are substantial reserves of sediment P in at least some parts of the lake.

Based on sediment features above, the upper 4 cm of sediment contain between 0.9 and 2.5 g P/m^2 of area. Not more than 10% of that total would be expected to be released in a summer season when exposed to low oxygen, but that would equate to 90 to 250 mg/m^2. With a water depth around 3 m (10 ft), that provides 3000 liters of dilution, and the concentration of P in the water column could increase by up to 30 to 83 µg/L, a very large increase. With about 20% of the lake bottom area experiencing this release, this concentration will be further diluted by fivefold for the lake overall, suggesting P increases of 6 to 17 ug/L. Even those increases represent a substantial risk of algae blooms, however.

Of particular concern is the potential for P to become available at the sediment-water interface and support growth of algae resting on the sediment. Blue-greens and filamentous green algae are especially known for this mode of growth; after some weeks of P uptake and growth with excess accumulation of P in cells, the colonies or filaments of cyanobacteria develop gas pockets in their cells and float upward to take advantage of more light. Synchronized rise of such blue-greens can result in blooms that seem to form overnight. Green algae mats form and capture their own photosynthetic gases, with those bubbles lifting the mats toward the surface of the lake. Even though P is not being actively mixed into the overlying waters by diffusion, the algae act as vectors of that P and promote ongoing blooms after the initial bloomers die and decay.

Table 6. Sediment features from Lake Shirley in June 2016

Lake Basin	Total Solids	Organic	Total Phosphorus	Iron Bound Phosphorus
Station	%	%	mg/kg dry weight	mg/kg dry weight
Upper	11	61.8	564	401
Middle	11	33.8	255	161
Lower	9.5	63.0	835	551

Plankton

Phytoplankton, or floating algae, were assessed from samples collected in 2015, 2016 and 2017. WRS collected or received samples in July through September in 2015, from June through August in 2016, and in May through September of 2017. Additional samples were provided by Lake Shirley volunteers or SOLitude Lake Management to Northeast Laboratories in 2015 and 2016, but the mode of analysis by Northeast Labs is not directly comparable to that performed by WRS.

Algae results from WRS (Figure 18) illustrate problems with blue-green algae (cyanobacteria) in 2015 but less so in 2016 and 2017. Algal biomass exceeded the probable problem threshold of 3000 µg/L for many samples in 2015, while no samples exceeded that threshold in 2016, although all values were above the possible problem threshold. Composition was dominated by blue-greens in 2015 and by a mixed assemblage in 2016, with greens and goldens most abundant by mass in 2016. The differences are likely to reflect nutrient input differences, but we have

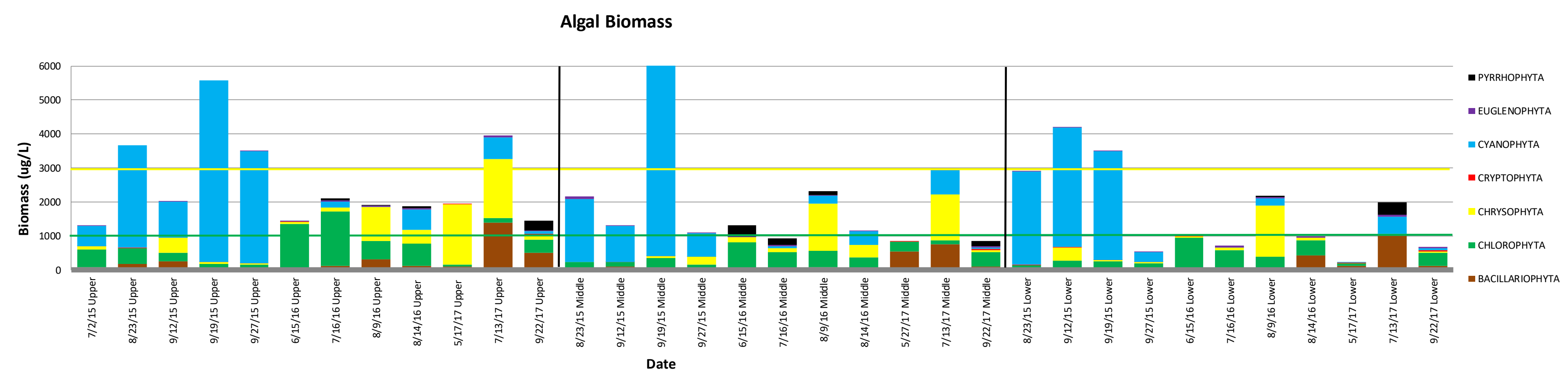


Figure 18. Phytoplankton in Lake Shirley, 2015 - 2017

nutrient data for only 2016, leaving the differences to speculation. In July of 2017 a bloom of the cyanobacterium *Dolichospermum* appeared to be developing, but Solitude Lake Management treated with copper and the bloom was prevented.

In 2015 there were multiple bloom-forming blue-greens that were abundant, including possible toxin forming *Dolichospermum* (formerly called *Anabaena*). In 2016, the most abundant blue-green was *Aphanizomenon*, which is a potential toxin producer but has not been known to produce toxins in northeastern USA lakes. In 2016 the more abundant algae were greens of the order Chlorococcales and the golden alga *Dinobryon*; the chloroccalean greens achieve highest abundance at elevated N levels, while the blue-greens tend to dominate when N is limiting. In 2017, golden algae and diatoms were most abundant in May, with cyanobacteria increasing in July before copper treatment. The September samples featured a mixed assemblage with green algae most abundant.

The Northeast Labs data do not provide a direct comparison, but do provide data from time periods in between WRS samples. Blue-greens were not nearly as abundant in 2016 as in 2015, but peaked in mid-July and prompted an algaecide treatment. Another small peak was observed in mid-August, but no treatment was conducted in response. Treatments in 2016 and 2017 may have avoided the major cyanobacteria bloom of 2015.

Zooplankton are small animals, mostly crustaceans, that live in the water column. Many eat algae and most are consumed by small fish as food. They are therefore an important link in the food chain. Zooplankton were assessed from the June and August 2016 and May, July and September 2017 sampling by WRS (Figures 19 and 20). Zooplankton included mostly copepods and cladocerans, both crustacean forms. Except for the lower basin sample in June, zooplankton biomass was low in 2016. Biomass was low in May of 2017, but increased markedly in July and September. Average body length was moderate for all samples in 2016 and for the May 2017 samples, but increased substantially in July and September 2017. Limited to moderate grazing capacity on algae and moderate food value for fish are indicated by the zooplankton community. Variability is high enough to warrant continued monitoring.

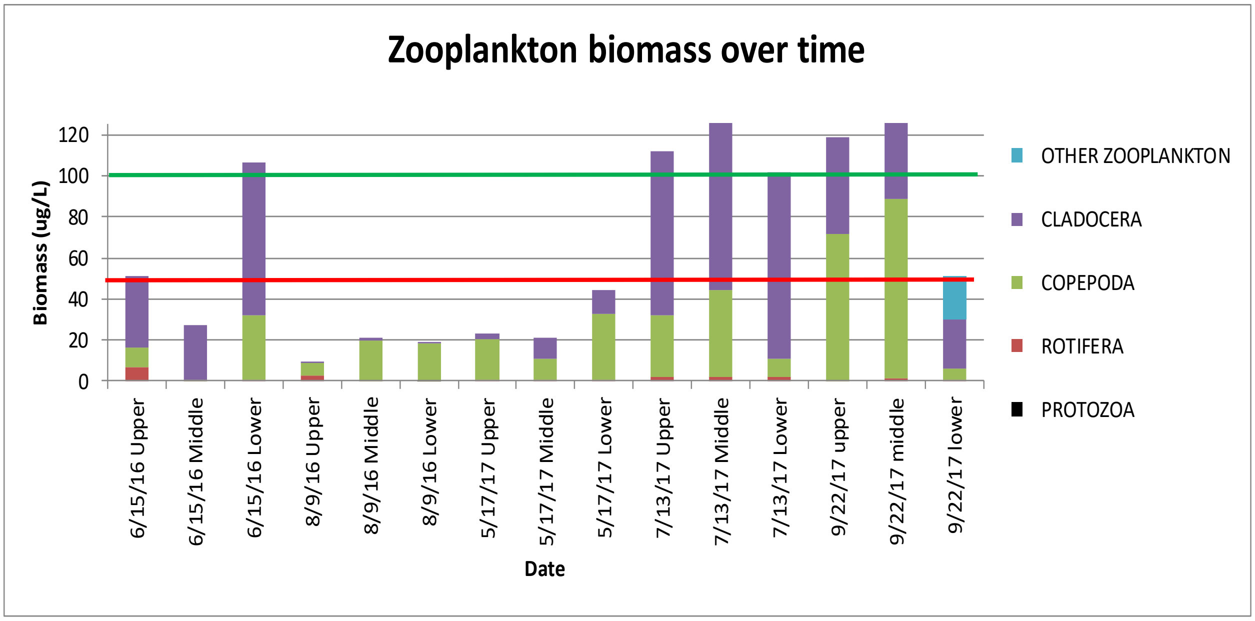


Figure 19. Zooplankton biomass in Lake Shirley in 2015 and 2016

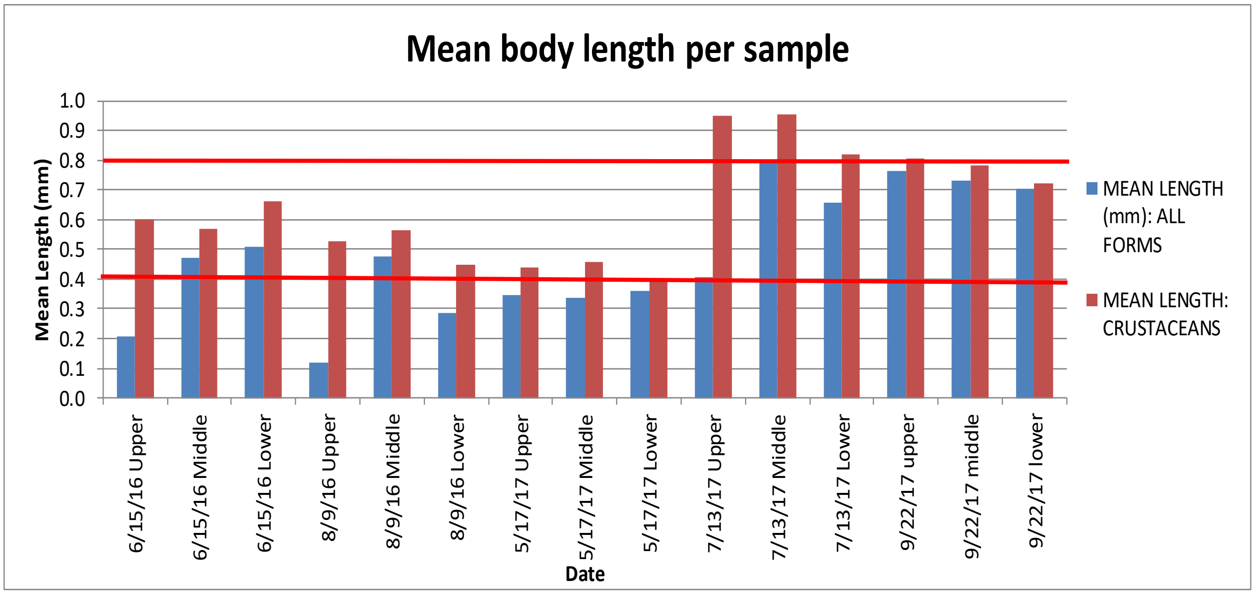


Figure 20. Zooplankton average length in Lake Shirley in 2015 and 2016

Nutrient Loading Assessment

While the results of the investigations of the last 3 years may seem plentiful, the spatial and temporal limits of the data restrict what we can do in terms of revisiting the loading estimates from past studies. Yet we have generated some new or updated estimates, and can work backward to evaluate loading of N and P to Shirley Lake in at least a preliminary manner. The key components (Figure 19) include the following :

1. Atmospheric deposition – Pollutants landing on the lake surface either with precipitation or as dryfall. This includes only direct inputs; airborne contaminants falling on the land or upstream lakes are processed as other inputs, such as overland flow (runoff). Direct atmospheric inputs constitute a large source only where the lake is large relative to the watershed, so we would not expect atmospheric loads to be dominant in this case.
2. Direct groundwater seepage – Pollutants entering with groundwater that directly enters the lake. Groundwater that enters a stream or upstream lake is accounted with the flow from that stream or lake and is not part of this element. This can be a major element where the lake is a kettlehole or seepage lake with no tributaries and located in sandy or rocky soils. This element may include wastewater from on-site disposal (septic) systems, which can raise the level of some contaminants substantially and are often split off by modeling efforts as a subset of this element. Lake Shirley could be subject to significant seepage impacts from nearby development, but the data suggest mainly N inputs, not substantial P loading.
3. Overland (surface) flow – Pollutants entering with surface water flows. These can be direct runoff from the immediate watershed or flows from streams that drain non-contiguous land areas. This also includes flow from upstream lakes to the target lake. This is often the largest loading element. Lake Shirley has a relatively large watershed (25 times the area of the lake), so there is a threat of substantial inputs with storms.
4. Discharges – Pollutants entering in any release that is not a natural flow channel, like a stream or lake overflow. This would include wastewater treatment facilities, cooling water, or other directed flows from human endeavors. This can be a major source of contaminants even with minor flows when concentrations are very high, but discharges are not a known influence on Lake Shirley.
5. Wildlife, mainly waterfowl – Pollutants released directly to the lake by birds, beavers, muskrats or other wildlife using the lake. Human inputs are not typically counted in this category. No flow is usually associated with wildlife inputs, but contaminant loads are often assigned based on the number of animal units present on a yearly basis. These are most influential in smaller ponds in settlings that attract many birds, like urban parks. We have not data for this category for Lake Shirley, but the impact does not appear to be great.
6. Internal loading – Pollutants that entered the lake from the above sources and are retained by the lake, usually by incorporation into the sediment, but are recycled and put back into the water

column. This can include release from the sediment, as with dissociation of iron and phosphorus under anoxia, release from plants after uptake from sediment as "leakage" or upon senescence, or stirring up of the bottom by wind or foraging fish like carp or catfish. This can be a major portion of the P load in lakes with long detention times, and as it is most often associated with summer, it may be disproportionately important in supporting algae blooms. The potential for this source to be influential in Lake Shirley is high, but past assessments have not indicated it as a major P source. It is rarely a major N source.

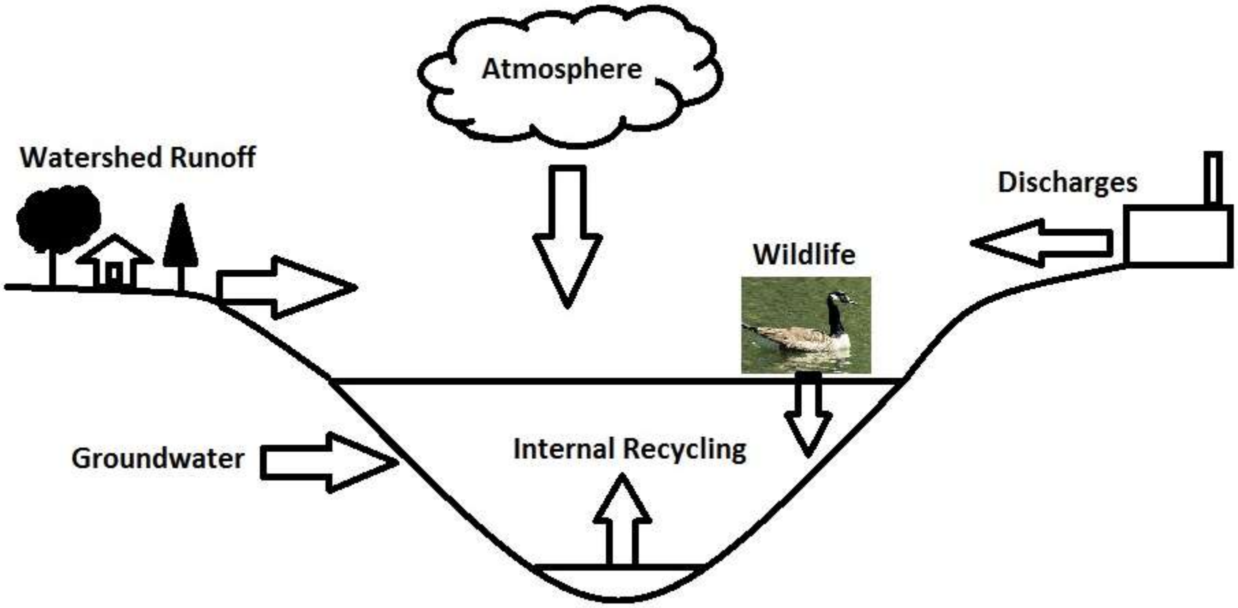


Figure 19. Contaminant loading schematic

A proper loading analysis considers each of the above source categories and works to bracket likely inputs associated with each. Often this involves first assessing the water load, then the concentration of associated contaminants, although it is possible to directly estimate loads as export coefficients based on direct measurements elsewhere, applied to land uses or lake area in the subject case. While no approach is better than direct measurement, the number of measurements necessary to adequately represent a source may be impractical to collect. Multiple approaches with consideration of the range of possible inputs are therefore often applied.

Atmospheric Deposition

On average, 1.1 meters of precipitation lands directly on Lake Shirley and the surrounding land every year; the precipitation landing directly on the pond provides about 1.6 milllion m^3/yr of water. Processing of precipitation that falls on land into runoff, groundwater, or evaporation is not part of this loading element; only the direct precipitation is addressed here. Average phosphorus concentration in precipitation varies over geographic area and with weather pattern (e.g., from the north, south, east or west), but is generally low in the northeast. Values measured by WRS staff in the past have averaged a little less than 20 µg/L, with values below 10 µg/L or as high as 50 µg/L possible. Particles containing phosphorus may fall from the sky even in dry weather, and may constitute as much as half the input, but much of these particulates will not contain readily available phosphorus and will become part of the sediment, the load from which is accounted for separately. N loading is typically 20 times the P load from atmospheric sources.

Applying a concentration of 20 µg/L to a rainfall of 1.6 million m^3/yr onto Lake Shirley, the total load of phosphorus from direct atmospheric input would be 32 kg/yr. The N load would be about 640 kg/yr.

Direct Ground Water Seepage

Groundwater seeps directly into the lake from surrounding land. Often this groundwater carries wastewater contaminants where on-site wastewater disposal systems are used, and can be an important source of phosphorus under certain conditions, but generally soil does an acceptable job of removing phosphorus. Farther from the lake, such groundwater may be intercepted by streams and become overland runoff, but some seepage into most lakes is expected. This can be measured directly with seepage meters, and samples can be taken with porewater samplers or from nearby wells to assess quality, and this investigation was accomplished in 2017 for Lake Shirley.

The seepage survey conducted by WRS resulted in a P load estimate of 20.5 kg/yr and an N load estimate of 1360 kg/yr. Much more N reaches the lake than P. The BSC (1999) study estimated that P reached the lake at a rate of 110 kg/yr, but this was not based on any actual data, just calculations using values from other systems. While the results of the single survey by WRS cannot be regarded as providing highly accurate loading estimates, it does appear that the BSC estimate is high and that on-site wastewater disposal is not a major source of P to the lake. That wastewater may be a substantial source of N, however, and this is consistent with many other studies in Massachusetts.

Overland Flow

Surface water flows enter Lake Shirley from two main tributaries, both entering the upper basin. Direct measurement of flow and phosphorus concentration in the tributaries feeding Lake Shirley has been conducted, but not at a level that would allow reliable application of concentrations and flows. It is the best we can do right now, however, and since surface water inflows are likely to be substantial nutrient sources, an effort is made here to estimate those inputs.

Using the area of the drainage basins for Catacoonamaug and Easter Brooks, with the remainder of the watershed taken as the difference between those two tributary drainage areas and the total watershed area of 9050 acres, and multiplying by the standard water yield for this area (1.0 cfs/mi^2), we get approximate total inflows of water from the 3 defined drainage areas (Table 7). Catacoonamaug supplies more than the water of the other drainages together, as it occupies 61% of the total watershed and the other two drainage areas represent about 20% each. The total water load from the watershed is estimated at about 12.6 million m^3/yr, very close to the 12.8 million m^3/yr estimated by BSC (1999). With the direct precipitation input of about 1.6 million m^3/yr and the ground water seepage of about 1 million m^3/yr, the total inflow to Lake Shirley would be 15.2 million m^3/yr, with surface flows dominating.

Table 7. Phosphorus and nitrogen loading from the Lake Shirley watershed

Watershed Source	Area (mi2)	Area (ac)	Area (ha)	Flow (cfs)	Flow (m3/yr)	Avg P conc (mg/L)	Avg N conc (mg/L)	P Load (kg/yr)	N Load (kg/yr)
Catacoonamaug	8.63	5521	2208	8.63	7709793	0.028	1.034	218	7968
Easter	2.69	1720	688	2.69	2403168	0.030	1.477	72	3549
Other drainage	2.83	1809	724	2.83	2528240	0.022	0.874	56	2208

The P and N concentration data for the surface water inputs are limited; additional data should be collected to refine this analysis. But based on what we have, and assuming that half the total water inputs will occur during dry weather and half in wet weather (wet weather happens 1/5 of the time, but provides 5 times the flow on average), the average P and N concentrations can be calculated from the available data and multiplied by the water load to get P and N loads (Table 7). Our best estimate for P loading from the watershed at this time is 345 kg P/yr and 13,726 kg N/yr, with Catacoonamaug Brook as the largest contributor.

With the uncertainty associated with flows and concentrations, there is a fairly wide margin of error for phosphorus loading from watershed sources. It is suggested that the load from the direct drainage area via overland flow will be about 206 kg/yr. It would not be surprising for annual loads to vary by at least 25% in either direction, based on precipitation pattern, which will drive non-point source loading from the watershed.

Additionally, some of the incoming load will be refractory particulates that do not directly contribute to the effective load; a loss of about 25% of the actual load to particulate settling might be expected. The concept of an effective load is important to grasp, as loading analyses should consider generation of a load at the source, any attenuation of that load on the way to the lake, and the form in which the load enters, which translates into its utility to algae and its immediate effect. Most analyses will tend to overestimate the effective load, as data for forms of phosphorus are often lacking. Many of the input sources may include some refractory (unavailable) phosphorus, but runoff inputs are most susceptible to this influence, as those inputs include soil, sticks, leaves and other matter that does not rapidly or easily give up associated phosphorus.

Discharges

We are unaware of any discharges to Lake Shirley. Here we refer to releases from activities subject to regulation as discharges under the Clean Water Act and related state statutes.

Wildlife

Studies of wildlife inputs of phosphorus to lakes have focused on waterfowl (Manny et al. 1975, Portnoy 1990, Scherer et al. 1995) and established a range of likely “exports” per bird per year, with variation based mainly on bird size (e.g., gulls vs. ducks vs. geese). If bird counts are available, one can estimate inputs with some degree of reliability. In the absence of counts, the exercise is highly speculative.

We are unaware of any bird counts for Lake Shirley. Assigning a fairly arbitrary number of 100 waterfowl being present for half the year, we have 50 bird-years. An average value of 0.2 kg P/bird-year is reasonable from the literature, yielding a bird-related P load of 10 kg/yr. For N, the average input is assumed to be 1.0 kg/bird-yr, so the estimated load is 50 kg N/yr. These estimates could easily be off by 100% in either direction, but as a relatively low load among the range of assessed sources, it does not warrant much additional effort. Further, bird management in a situation like that at Lake Shirley is difficult and in some ways counterproductive; the presence of birds is considered an asset by many lake users.

Internal Loading

Internal loading can involve multiple processes. Plants pull nutrients from the sediment and may either leak some of those nutrients into the water column or release them upon typical fall senescence. Bottom feeding fish or wind in shallow area can resuspend sediment and processes in the water column may make some of the associated nutrients available. Decay of organic matter in shallow water may release P into the water column, and this can be a significant source where highly organic sediments are found in shallow water with adequate oxygen to support decay. Most often, however, substantial internal loading is a function of release of P from iron complexes under anoxic conditions near the sediment-water interface. This tends to happen in deeper water, below the thermocline, but can occur anywhere that the surficial sediment goes anoxic. Anoxia arises when oxygen consumption exceeds the rate of resupply. Even with adequate oxygen in the overlying water column, sediments can experience anoxia and release P from iron compounds.

Release of P from iron-bound forms in surficial sediments is a function of the concentration of iron-bound P and the extent and duration of anoxia. Once stratification begins, replenishment of deep water oxygen is strongly curtailed, while decomposition accelerates as temperatures rise. Oxygen near the bottom is used up first, with the anoxic interface rising from the bottom as oxygen is consumed and not replaced. As that anoxic interface rises, more sediment area is exposed to anoxia and iron-bound phosphorus may be released. The actual release process is a function of redox potential, the intensity of electron stripping from available compounds, preferentially oxygen, but later nitrate and eventually sulfate. While oxygen can only decline to a concentration of zero, redox potential can continue to decline, going negative, increasing the rate of P release even after oxygen is depleted.

In Lake Shirley, thermal stratification is weak over most of the lake, with just an 11 acre area in the lower basin having a truly separate bottom layer in summer. The maximum temperature difference between the pond surface and bottom is often too small (<3 C^{o}) to resist wind mixing. Yet we found low oxygen when the oxygen probe is placed in contact with the bottom sediment in water deeper than about 9 feet, so anoxia does occur at the sediment-water interface, but any released phosphorus may be subject to oxidative reactions before it moves upward very far.

In a relatively shallow waterbody, algae blooms that depend on internal recycling of P can still be expected, as light in all but the deepest water is adequate to allow green algae mats or cyanobacterial colonies to grow at the sediment-water interface and then float upward. Many cyanobacteria initiate growth on the bottom, then form gas pockets in their cells and rise to the surface almost synchronously. Those cells tend to carry excess P, and once in the upper waters the algae can grow with adequate light. When cells die, some portion of the P is released into the upper waters and can support other algae growth. Blooms that start on the bottom and move to the surface are therefore not just symptoms of increasing fertility but vectors of it. The cyanobacteria blooms in Lake Shirley may get their start this way, but the elevated P levels in the water column may support those blooms for longer than is sometimes observed in other lakes where deep water P is elevated but surface water levels are low.

The area of potentially significant P release is linked to the zone of anoxia, but the rate of release may vary substantially over space and time within that zone and defining that zone is difficult in a polymictic lake (one that stratifies weakly or not at all and can mix often in response to wind). Areas may contribute P off and on over the year. This complicates calculation of phosphorus release. The lack of a distinct bottom layer where phosphorus accumulates further impedes estimation of release rates.

One can apply literature values for release rates, but this is more speculative. However, use of literature values as a reality check on estimates from a lake can help validate results; most anoxic sediments with significant levels of iron-bound phosphorus will release at least 1.0 $mg/m^2/day$, while sediments exposed to anoxia for longer periods may release phosphorus at levels in excess of 12 $mg/m^2/day$. Another approach involves assessing the mass of iron-bound phosphorus in surficial sediments that might be subject to release and estimating releases as a percentage of that total. Finally, cores can be collected and incubated in a lab with measurement of phosphorus levels in the overlying water at the start and end of the incubation period to determine release rates under varying levels of oxygen presence or duration of anoxia.

The concentration of iron-bound phosphorus in the uppermost layer of sediment was assessed for each of the three basins with one sample each, which yielded values of 401 (upper), 161 (middle), and 551 (lower) mg P/kg dry weight sediment. Based on solids content and related sediment features, the mass of P expected in the upper 4 cm is estimated at 0.9-2.5 g/m^2. This is a rough estimate that should be refined with additional testing if internal load management is pursued, but provides an estimate of how much phosphorus is available per unit area. It would be expected that no more than 10% of that P would be released in any one year, based on experience elsewhere. For the area of the lake deeper than 9 feet (about 70 acres, or 280,000 m^2), this suggests a possible release of 25 to 70 kg each year, mainly during summer.

A load of 25 to 70 kg/yr from 280,000 m^2 over a period of 100 days would equate to an average release rate of 0.9-2.5 mg/m2/day, which is within the expected range based on extensive assessments in other lakes.

N loading from internal sources has not been investigated for Lake Shirley, but is usually 3-7 times the P loading from internal sources, and is not often a major source to lakes. For Lake

Shirley, an estimated range of 125 to 350 kg/yr is suggested. Even the highest conceivable N load from internal sources of 490 kg/yr is low in comparison to other sources to this lake.

Loading Summary

The water load is divided between direct precipitation, overland runoff from three defined drainage areas, and groundwater inseepage (Table 8). The surface load of water from the watershed is clearly dominant, with Catacoonamaug Brook as the largest itemized source. This dominance in water load carries over to the P and N loads, where it represents close to half of the total load to the lake. Easter Brook is next largest among source of P and N, but is slightly less of a water source than the remaining part of the watershed (exclusive of drainage to Catacoonamaug Bk). Internal loading is the next largest source of P after the three surface watershed drainage areas, but ground water is the next largest source of N after the surface watershed. All other sources are minor and not likely to be relevant to lake management.

Table 8. Water, phosphorus and nitrogen loading summary

Source	Flow (m3/yr)	Flow (%)	P Load (kg/yr)	P Load (%)	N Load (kg/yr)	N Load (%)	N:P Load Ratio
Watershed							
Catacoonamaug	7709793	50.6	218	47.9	7968	49.8	37
Easter	2403168	15.8	72	15.7	3549	22.2	50
Other drainage	2528240	16.6	56	12.2	2208	13.8	40
Atmospheric	1557000	10.2	32	7.0	640	4.0	20
Ground water	1032000	6.8	21	4.5	1360	8.5	66
Wildlife	0	0.0	10	2.2	50	0.3	5
Internal	0	0.0	48	10.4	238	1.5	5
Total	15230201	100.0	455	100.0	16014	100.0	

The total P load from this investigation (455 kg/yr) is lower than the loads estimated by M&E and BSC in 1986 and 1999, respectively, which formed a tight range of 652-664 kg/yr. The in-lake P concentration given in those studies ranged from 30 to 60 µg/L, while the average from 2015-2016 measurements was 22 µg/L. Whether past measurements and calculations were off or the load and in-lake concentration have actually been reduced over the last 20-30 years is unknown. Yet all paired loads and concentrations for P correspond well when applied in models that predict either concentration from load or load from concentration.

While more monitoring data would be helpful, the current status of the lake with a P load of 455 kg/yr and an average surface water concentration in the lake of 22 µg/L is believable and consistent with observations. A concentration of 22 µg/L is high enough to support blooms, but given variation over time, would be expected to lead to variable conditions with regard to algae in the lake. That is what we see over time; some periods of acceptable clarity and others of low clarity with quantified algae blooms.

Determining a desirable P load can be done with models too. If an in-lake P concentration of 10 µg/L could be achieved, algae bloom potential would be greatly diminished. That would require an approximate halving of the current load. There might still be issues with algae growing at the sediment-water interface and floating upward, but reducing the P load and in-lake concentration would be major steps toward minimizing algae proglems.

The N load from past studies was estimated at slightly more than 10,000 kg/yr, while the load in this study was estimated to average slightly more than 16,000 kg/yr. Applying the load in the available empirical models, the predicted N concentration in the lake should be close to 0.8 mg/L, while the actual concentration from 2016-2017 data was 0.46 mg/L. Undoubtedly much of the N load from the watershed is particulate (leaves, sticks, soil) and largely refractory (does not easily decay and get released) and will settle to form the organic muck observed in the lake but not figure into N concentrations in the overlying water. The N load experienced by the lake, backcalculated from the in-lake concentration, is about 9330 kg/yr.

The ratio of the apparent total N and P loads is about 20:1, in between what would be expected to promote cyanobacteria vs what would favor green algae. With variation over the course of the year, the ratio may deviate in favor of one or the other. In the spring, with higher flows from the watershed (which have high N:P ratios, Table 8) would be expected to favor green algae, or golden algae and diatoms when combined with colder temperatures. But in summer, with much lower watershed loading and the entire internal and wildlife loads being added, the N:P ratio will be much lower. The N:P ratio for water in the deepest part of the lower basin is about 8:1; if a similar ratio prevails at the sediment-water interface wherever oxygen is low, that would favor growth of cyanobacteria in those areas. Again, variability over time and space will make predictability difficult, but the processes at work can be understood. How we might control them to get the best conditions becomes the central question for lake management.

Diagnostic Conclusions

Lake Shirley is a moderately sized (354 acre) lake with 3 defined basins but many coves and generally shallow depth. It has a large watershed (>25 times the area of the lake), resulting in generally large but temporally variable water inputs. The potential for variable conditions over the lake area and over time is very high, making it hard to monitor effectively and inexpensively in support of management decisions and expenditures. Effort over 3 decades has improved our understanding of this lake, but there are aspects that have not yet been well enough assessed to draw clear conclusions. This summary seeks to outline key information we now possess that can aid management.

The average in-lake surface water P concentration is 0.022 mg/L (22 µg/L) from 2016-2017 sampling. This is at the threshold for support of algae blooms on a frequent basis, but variation over time and space in Lake Shirley suggests that corresponding algae growth will also be variable. The average nitrogen concentration is about 0.5 mg/L, a moderate value, and variation in the N:P ratio also suggests that different types of algae will be favored over space and time. Water clarity tends to hover around 2 m and rarely exceeds 3 m. There is a gradient of conditions from upper through lower basins that suggests the worst conditions occur in the upper basin, where most watershed loading occurs.

The pH is near neutral but slightly higher than would be expected as a natural background for this area, probably as a function of rooted plant and algae growth, which raise pH through photosynthetic activity. Alkalinity is near the threshold between low and moderate ranges (near 20 mg/L) and conductivity is slightly elevated (240-310 µS) for this area but not high, possibly a consequence of road salt build-up. Turbidity is variable but mostly moderate (3-8 NTU), yet still higher than desirable for optimal lake conditions.

The main surface water inputs come from two tributaries to the upper (northern) basin, Easter Brook and Catacoonamaug Brook, the latter draining more area and having more influence on the lake. Additional smaller inputs exist, notably the wetland near Reservoir Road west of the upper basin, and possible overflows from wetland areas around the other basins and direct runoff from adjacent developed parcels, but >75% of all surface water inputs will enter the north basin and move through the lake from there. With a detention time of 2-3 months, water from the upper basin will move through the system with some regularity. Flows will decline over summer and into early fall, but what comes from the watershed, especially during storms, is enough to determine most aspects of water quality in Lake Shirley most of the year. Some coves are more isolated, however, and may not flush nearly as often as simply dividing the lake volume by the rate of inflow would suggest. There is also a small area (11 acres) of the lower basin that is deep enough to stratify strongly enough to create a separate water layer during summer. That layer is subject to very low oxygen and build-up of ammonium N and available P, but represents only a small volume (<6%) of the lake.

Based on limited monitoring, nutrient loading tends to follow the flow in this system, and the two main tributaries account for almost 2/3 of the P load and slightly more of the N load. Remaining surface water inputs account for another 12-14% of P and N loading. Internal loading is the next largest itemized source of P (10%) after watershed loading from surface flows, while ground water seepage (9%) is the next largest source of N after surface water inputs. The total load of P is about twice what would be desirable to minimize the potential for algae blooms, but enters in a temporally variable pattern with changing N:P ratio that most favors cyanobacteria in mid- to late summer. To cut P loading on half, it will be necessary to address watershed surface water loading, as most of the P enters with surface water, especially storm water runoff.

Water clarity is lowered by algae blooms, but is also reduced by organic particles resuspended by wind or boat action acting on sediment in this generally shallow lake. With low oxygen at the sediment-water interface over at least 70 acres (>9 feet deep) of Lake Shirley and substantial P in that sediment that becomes available at low oxygen levels, algae may grow well at the sediment surface over all but 11 of those 70 acres that are too deep for light to support algae growth. Those algae can then float upward, causing blooms; many cyanobacteria and filamentous green algae utilize this mechanism of bloom formation. It is also possible that decomposition of organic matter facilitates algae growth near the sediment-water interface in areas <9 feet deep. Even if watershed inputs are curtailed, it may also be necessary to address P availability in bottom sediments to control algae blooms.

From limited monitoring, ground water does not appear to be a significant source of P to Lake Shirley. On-site wastewater disposal does not appear to be contributing substantially to P loading of Lake Shirley, but N loading from ground water is larger and is likely a consequence of on-site wastewater disposal. This is consistent with findings in many other Massachusetts lakes.

Plant conditions were not evaluated as part of the WRS effort, but past surveys have detected at least 5 invasive species and several native species that can grow to nuisance densities. A drawdown is conducted in most winters to enhance plant control, and the main problem plants in Lake Shirley are susceptible to drawdown, so this may limit but not eliminate the need for herbicides. We are unaware of any evaluation of the most advantageous target depth for the drawdown, impact assessment, or refill calculations.

SOLitude assesses plants and to some extent algae in most years, and recommends and carries out any treatments. At least one herbicide and one algaecide treatment were conducted in each of 2016 and 2017, and algae biomass was much lower than observed in 2015 when cyanobacteria blooms were severe. Herbicide treatments to control rooted plants have maintained desirable conditions over much of the lake, but can release nutrients during the summer that could support increased algae growth. Major algae blooms are not often associated with plant die off, but some increase in algae is to be expected and could be a factor in Lake Shirley. We may be trading rooted plant problems for algae problems in some cases, necessitating management of both types of nuisances.

Management Considerations

Management choices embody science (will it work?), economics (can we afford it?) and sociopolitical elements (can we get a permit and will the action be acceptable to the user community?). This assessment really only deals with the scientific aspects of lake management, but the other factors are at least as important.

The breakdown of P and N loading indicates that meaningful reductions will have to come through watershed management, and that the two main tributaries, Catacoonamaug and Easter Brooks, are the primary targets. Certainly optimal management of shorefront properties could lower nutrient inputs, but with the two main tributaries accounting for 64% of the estimated P load and 72% of the estimated N load, meaningful reductions will need to focus on the land draining to those tributaries. An appealing alternative to watershed management is to treat each tributary near the point of entry to the lake with a P inactivator, like aluminum, dosing inputs during periods of high flow, mainly during storm events. It is philosophically more appealing to manage inputs near their sources, but it would be more expedient, less expensive, and more effective to treat the incoming water.

Surficial sediment as a source of P cannot be ignored, however, as algae can make efficient use of this source and considerable P-rich sediment has built up over many years in Lake Shirley. Inactivation of surficial sediment P is a well-documented approach, with aluminum the most common P inactivator. An area of at least 70 acres would need to be treated (all area >9 feet deep), and treatment of a greater area might be desirable, but data to determine the precise extent of a target treatment zone are currently lacking; more sediment testing would be needed. The extent of in-lake treatment necessary to control algae blooms is uncertain, however, and attention should probably first be focused on reducing watershed loading of P.

The other aspect of surficial sediment that is problematic is the resuspension of organic particles by wind and boat activity. With an average depth of just over 7 feet, wind or motorized watercraft will cause sediment resuspension, and low density organic matter may remain in the water column for days at a time, creating turbidity additional to that caused by algae. It is not clear how much of this effect is due to wind and how much to boats, but observations during sampling trips did indicate that boats were a factor. Checking turbidity on a daily basis during weekdays and weekends, during sunny weather and rainy periods, and during windy conditions and calm days is not difficult and would elucidate the relative roles of weather and boats on non-algal turbidity. Such studies have been conducted elsewhere with variable but conclusive results.

If sediment resuspension is to be reduced, either the factors causing the resuspension might be regulated (boats only, as wind is not subject to management), or the sediment could be removed to a point where induced mixing does not reach the sediment surface. Dredging would represent true restoration of Lake Shirley, and might solve multiple problems (sediment resuspension, excessive plant growth, some algae blooms), but is very expensive and not easy to permit in Massachusetts.

Rooted plant nuisances and algae blooms can also be attacked directly through herbicides and algaecides, and those have been mainstays of recent management in Lake Shirley. The use of herbicides by has not been excessive, partly from concern over impacts through the permit system and partly due to cost, and control of rooted plants has not been extreme. Habitat value for fish and other water-dependent organisms does not appear to have been compromised, although no detailed studies have been conducted. The lake is certainly not devoid of plants. Use of copper as a control on algae, especially cyanobacteria, has been conducted fairly scientifically over the past two years, with algae concentrations tracked and copper applied before a bloom has truly formed. In both 2016 and 2017 a single, well-timed treatment prevented major cyanobacteria bloom formation. Failure to treat in that manner allowed a major cyanobacteria bloom in 2015.

Peroxide-based algaecides could be considered in place of copper, but there is little risk of collateral damage from copper in this system with one treatment per year. Reducing nutrients, especially P, is the preferable strategy, but will be more costly and take longer than use of algaecides. Maintaining the option to use an algaecide while working toward P control is a sound strategy.

Adjustment of the management plan put forth by SOLitude in 2017 will require discussion by the LSIC and the regulatory community, consideration of funding sources, and additional planning. Some form of P control for the two main tributaries discharging to Lake Shirley should be the top longer term priority, with herbicides, algaecides, and possibly P inactivation for surficial sediments used as interim and supplemental methods. The drawdown may be a useful management tool as well, but we do not have enough information to properly evaluate all aspects of drawdown at this time.