Leonard Lake:
Water Quality and Algal Blooms

Status, Monitoring and Management

Prepared for the
Leonard Lake Stakeholders Association (LLSA)

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*cover photo of Leonard Lake, winter 2017, by Mark Scarrow, LLSA

EXECUTIVE SUMMARY

The Leonard Lake Stakeholders Association (LLSA) report *Leonard Lake: Water Quality and Algal Blooms: Status, Monitoring and Management* was commissioned by the LLSA as part of their stewardship programme aimed to monitor and protect the integrity and quality of this lake. The report first provides a comprehensive synopsis of previous information on Leonard Lake (LL) generated by a number of earlier studies and monitoring programmes by different agencies, including lake morphometry, background information and historical monitoring data. The second section of the report describes the rationale, operation and results of an intensive LLSA water sampling study conducted between May and October 2017. This study was undertaken to assess current lake status and vulnerability to the effects of human activities and shoreline development, and develop more effective ongoing monitoring and stewardship programmes in partnership with regional and provincial agencies.

Leonard Lake is representative of many small lakes in Muskoka, with relatively clear water, low buffering capacity and low nutrient levels (oligotrophic). The lake's characteristics as a head-water lake with a small water catchment area, thin, acidic soils, and rocky, often steep shoreline serve to limit nutrient loadings from natural sources, but also make the lake more sensitive to degradation from shoreline changes and development.

Initial surveys and modelling dating back to 1971 by the Ontario Water Resources Commission (OWRC) describe LL as "*moderately enriched*" but also reported thick algal mats in the southwestern end where early cottage development had occurred. Since 1971, developed lots have more than doubled to 167, and based on the geology and topography of the shoreline and catchment, the OWRC concluded that the lake was "*largely unsuited for cottage development with subsurface septic systems*." In 2005, a review by Gartner Lee classified LL as "*above the threshold level of enrichment with a moderate sensitivity to development capacity…based on Total Phosphorus (TP) using the District of Muskoka Recreational Water Quality Model".* This provided some level of protection from shoreline development. TP levels monitored by several agencies[a] at a central offshore site in LL indicate no significant long-term change in LL water quality, however, the District of Municipality of Muskoka (DMM) has recently proposed to initiate recommendations in the HESL (2016) report[b] which effectively remove this protection and reclassify Leonard Lake as warranting only "normal" protection from further lot development.

[a] including the District Municipality of Muskoka (DMM), the Ontario Ministry of the Environment and Climate Change (MOECC) and Ministry of Natural Resources (OMNR), the provincial Lake Partnership Programme (LPP), and Muskoka Lakes Association (MLA).

[b] District of Muskoka Recreational Water Quality Model Review June 2016

Extensive monitoring by the MOECC between 1979 and 2016 revealed no overall change in TP measured at a single mid-lake location, but a gradual decline in water clarity and increase in dissolved organic carbon. During this period, chlorine and sodium levels almost quadrupled, possibly due to the use of road salt, demonstrating the vulnerability of Leonard Lake to runoff from roads. During late summer, dissolved oxygen levels near the lake bottom often declined to zero or very low levels ('anoxic' or 'hypoxic'), and Nurnberg (2017) recently highlighted the potential vulnerability of the lake to the release of nutrients from the bottom sediments due to depleted oxygen[c]. Internal loading is also generated by direct sediment resuspension from motor boats in shallow areas and exacerbated by the long residence time of water in Leonard Lake. Cyanobacteria (aka 'blue-green algae') were present in low abundance in historic MOECC samples but toxic producing species were not detected.

Leonard Lake has been monitored extensively by several agencies over the last half century and the availability of data spanning several decades provides an excellent opportunity for review and a useful base for interpreting the 2017 study results. However, comparison among data sets collected by these agencies is greatly hindered by differences in monitoring protocols, and future collaborative work should first work to institute common protocols and re-evaluate monitoring sites (see below) to improve the compatibility and value of water quality monitoring in Muskoka.

Anecdotal reports of increased algal blooms in Leonard Lake over the past few years indicated a potential decline in water quality and a need to expand lake monitoring, and with the identification of cyanobacteria-dominated surface and below surface blooms in neighbouring lakes in the region, there was concern and a sense of urgency for a detailed study of Leonard Lake. Between May and October 2017, members of LLSA carried out extensive water chemistry and phytoplankton sampling at several mid-lake and near-shore sites on LL.

The major results of this study showed that Leonard Lake has a low to moderate level of biomass growth and a diverse algal community dominated by lipid-rich diatoms and flagellates (high quality food for the upper food-web) and small cyanobacteria and green algae, indicative of an oligotrophic (nutrient poor) transitioning to a mesotrophic (moderately enriched) lake. A number of major concerns were identified:

- Nutrient[d] levels (total phosphorus (TP), total dissolved P, and dissolved inorganic nitrogen (N)) measured at different depths at four sites in the lake over the season were highly variable, and often exceeded the long-term averages measured by the provincial and regional agencies who have largely concentrated on spring samples collected over the entire water column at a single mid-lake location.

[c] This release from lake sediments is termed 'internal nutrient loading'.
[d] Essential nutrients for plant and algal growth (in most North American lakes these are usually P and N); a low supply means low algal growth.

- Low levels of noxious bloom-forming cyanobacteria such as *Dolichospermum* were present across much of the lake for most of the sampling period. While the background presence of these cyanobacteria is typical of low nutrient lakes, they are opportunistic and can develop localised blooms in response to nutrient influx e.g. from shoreline septic systems. Furthermore, some strains of these species can produce potent toxins that can have serious effects if ingested by pets, other animals and birds, or humans.
- In the summer of 2017, an LLSA "Eyes on the Lake" campaign resulted in 10 reports of possible near-shore bloom sightings. These were quickly sampled by LLSA volunteers and dispatched for species analysis. Four of the samples collected in mid-September from surface scums were composed largely of *Dolichospermum*, which has been reported as a toxin producer in other lakes.[e] Public awareness and reporting of algal blooms has escalated and can exceed laboratory and field capacity for timely sampling and analysis of these events, which can form and disperse rapidly. During September 2017, LLSA contacted the Spills Action Centre three times to report a scum. MOECC sampled a single site, but could not do so until after the bloom had disappeared.
- Sampling revealed significant vulnerability to low dissolved oxygen levels in bottom waters at several sites across the lake. This has implications for both internal loading and the degradation of fish/aquatic invertebrate habitat, particularly cold-living species which may migrate to these bottom sites.
- Appreciable seasonal and spatial variance in algal biomass and species composition, and a vulnerability to inshore blooms, is underrepresented by current agency monitoring programmes. In the current climate change scenario, this vulnerability is predicted to increase.

RECOMMENDATIONS

LOT DEVELOPMENT

Issue: Size, morphometry, low flushing rates, bottom oxygen depletion and cottage development mean that Leonard Lake is vulnerable to the impacts of current and further development, particularly with the current warming trends in climate. (Nurnberg 2017)

Actions: Consider a moratorium on further lot severances while continuing water chemistry and phytoplankton testing and monitoring for blooms. Restrict shoreline development to maintain a vegetated buffer strip and minimise runoff from lawns, roads etc. Maintain high vigilance on the capacity, age and status of septic and other wastewater systems.

MONITORING PROTOCOLS

Issue: Current protocols concentrate on spring samples collected as surface-bottom composites and fail to capture the significant spatial[f] and seasonal variance in water quality, nutrients

[e] Resources were not available for toxin analysis in 2017
[f] Inshore-offshore, surface scums, deep-living algal maxima

and algae exacerbated by activity, boat traffic, severe storms, etc. Seasonal averages are unlikely to provide a robust assessment of the full range in lake-wide nutrient and algal biomass levels.

Issue: The seasonal and spatially-resolved phytoplankton data represent a vital resource against which future change can be assessed, which if possible, should be continued along with an assessment of water quality and particularly, inshore and internal nutrient loading.

Action: LLSA should work with the DMM, MOECC and MLA to review testing protocols for Leonard Lake and other Muskoka lakes including site location, frequency and type. LLSA will continue to engage lake residents to report incidents of scum, blooms, etc. and to develop lake procedures regarding incident reports, collection and dispatch of samples.

ANOXIA AND HESL "39 CANDIDATE ANOXIC LAKES"

Issue: Oxygen profiles show a significant decrease towards the sediment surface which in many years are anoxic or hypoxic; however, Leonard Lake was not included in the 39 Candidate Anoxic Lakes identified in the recent HESL (2016) report and further sampled for internal loading. Lakes in the '*above-threshold, moderately to highly sensitive'* categories (e.g. Leonard Lake) should be further assessed for soil composition, depth and P retention.

Action: The DMM should add Leonard Lake to the 39 Candidate Anoxic Lakes and further sample LL for internal loading.

Action: The LLSA board consider ways of increasing awareness among stakeholders concerning the impacts of motor boats on lake health.

DATA COMPATABILITY

Issue: At present, Leonard Lake is monitored by five agencies or government departments, often using different protocols, resulting in redundancy and incompatible data. This greatly impedes the interpretation of these data and represents a waste of scarce resources.

Action: That LLSA should request the key agencies (e.g. DMM, MOECC) to evaluate discrepancies in site locations, redundant sampling efforts and differences between agencies in sampling and analysis, and work with the LLSA to develop common protocols to maximise the valued outcome of these efforts.

SEPTIC SYSTEMS

Issue: The efficacy of current septic wastewater systems on Leonard Lake is unknown. Septic loading can represent a significant proportion of the total external load to a lake.

Action**:** That LLSA should continue to maintain close liaison with the DMM regarding lake septic and wastewater testing and evaluation to ensure that systems on LL meet municipal and provincial specifications and are monitored to insure full compliance.

CYANOBACTERIA ('BLUE-GREEN ALGAE')

Issue: The revised Muskoka Lake Health System Update stipulates "*Blue-green algal cyanobacteria blooms as documented by public complaints to the MOECC or the Simcoe-Muskoka District Health Unit*," as one of three metrics identifying "special status" lakes.

Issue: Cyanobacteria blooms were identified in LL at several shoreline sites in 2017, but the LLSA was unable to test these for toxicity. In addition, the MOECC and Simcoe Muskoka Health Unit could not mobilise quickly enough to confirm the presence of these blooms.

Action: A bloom response protocol with speed of service standards should be established collaboratively between provincial (MOECC), District and local (Simcoe/ Muskoka Health Unit), and Lake Associations (including MLA) to ensure a rapid, timely response and rigorous assessment of toxins and other risk factors. The protocol could include training at the lake or lake association level in sampling and dispatch protocols, to address the need for timely sampling. In addition, a toxin analysis protocol should be established.

Expertise and taxonomic analysis was provided by the authors of this report, Dr. Sue Watson, University of Waterloo, Department of Biology and Hedy J. Kling, MSc., Algal Taxonomy and Ecology Inc., Winnipeg. Field and lab support were provided by Mark Verschoor, MSc., York University, Department of Biology and Dr. Mingsheng Ma, Laboratory Manager, Biogeochemical Analytical Service Laboratory, University of Alberta.

Leonard Lake

Background

Leonard Lake (45.0751, -79.4496) is a headwater lake in a small catchment area (4.19 km^2) in the Algonquin-Lake Nipissing ecoregion of the Boreal Shield Ecozone (CCME 2006; DMM 2015). The catchment is composed of Precambrian bedrock covered by a thin (< 1.5 m deep) layer of granitic loam sandy till with rocky outcrops. Surface water inputs occur largely from precipitation, direct runoff and small streams; the contribution of groundwater is unknown. It has a shallow south

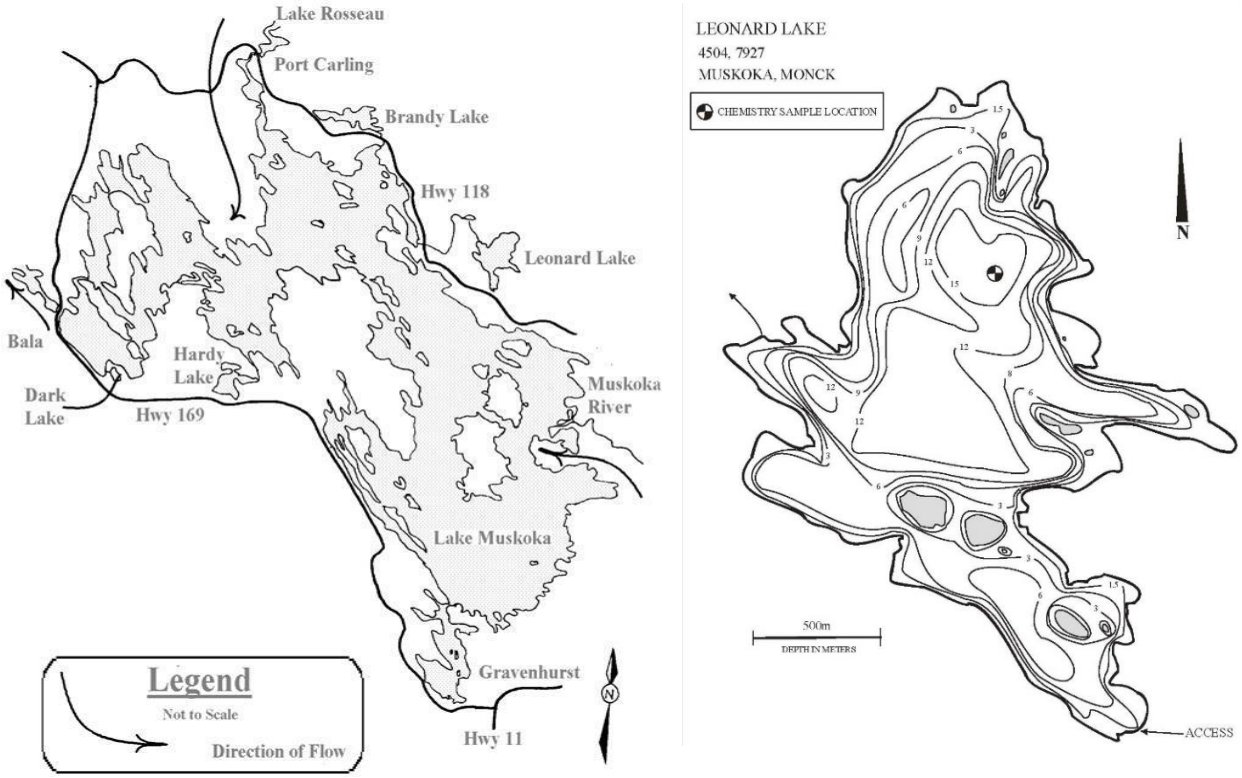

Fig 1. Location (left) and bathymetry (right) of Leonard Lake

basin which is generally < 6m deep, and a deeper northern segment (maximum depth 16-17.5 m; DMM 2015; Ingram and Paterson 2015; Table 1; Fig 1) which develops seasonal bottom oxygen depletion (detailed below). A single small outflow at the western side has a discontinuous flow into Milford Bay, Lake Muskoka, and the lake has a long turnover rate with ~ 20% of the total volume renewed each year and an estimated residence time of 5.4 years (Nurnberg 2017). Leonard Lake has a complex shoreline morphometry, largely composed of exposed bedrock or stones with a few proximal or shoreline wetland areas (Table 1; Fig S-1).

Leonard Lake has a low buffering capacity, typical of softwater shield lakes, as shown by the impacts of the acid precipitation of the mid-late 1900s on the pH, which reached a low of 5.5 in the early 1980s and have shown a very slow recovery to current levels around 6.5. This important characteristic affects the abundance, composition, and productivity of the aquatic biota. During the recovery, there has been a gradual concomitant decrease in sulphate and increase in dissolved organic carbon (DOC) from ~3 mg/L to ~4.5 mg/L, within the range typical of this Ecozone (3.9-4.7 mg/L; Fig. 2; CCME 2006). This increase was attributed by the Ontario Ministry of the Environment and Climate Change (MOECC) to climate-related increased basin inputs from soil and detrital turnover (Ingram and Paterson 2015), and likely resulted in a change in the penetration and spectrum of light in the water column.

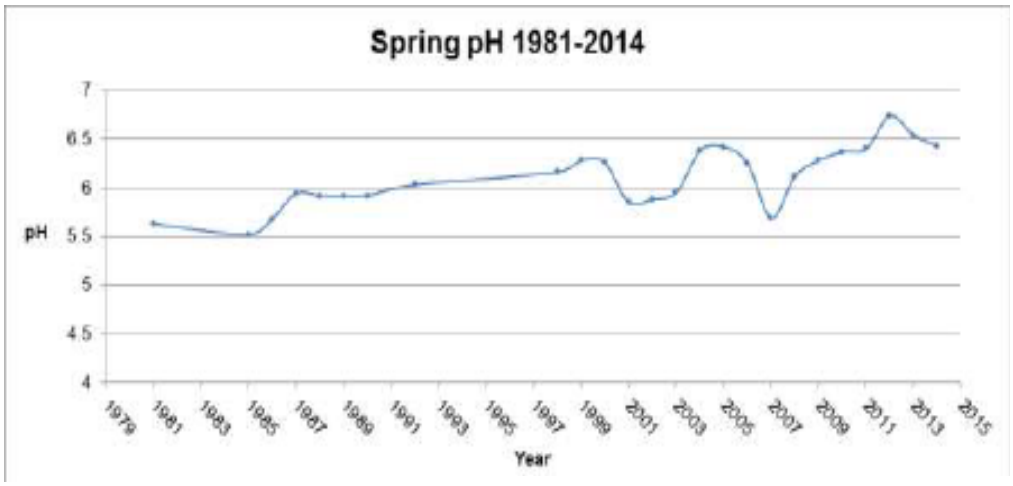

Fig 2. Long term trend in pH measured at the central monitoring site in Leonard Lake; from Ingram and Peterson (2015)

Water clarity is generally high in Leonard Lake, with spring secchi depth (SD) between 3 – 4.5m. This would support photosynthetic activity down to a depth of approximately 7.5-9m[1], and provide an extensive littoral area for the growth of aquatic plants and benthic algae, particularly in the south basin. These areas are also important habitat for invertebrates, fish and other aquatic and terrestrial organisms and can often represent the predominant fraction of the lake productivity (Vadeboncoeur et al. 2002).

The vulnerability of Leonard Lake to runoff from roads is demonstrated in the significant rise in chloride levels from road salt over the past few decades, increasing dramatically since the late 1970s. Proximity to roads can have major impacts on water quality, aquatic food-webs, and the ecological services provided by lakes as a result of pollution (heavy metals, sediment, organic

[1] assuming the commonly used measure of the photic zone as 2.5 x secchi depth

pollutants), habitat disruption, erosion etc. (e.g. Transportation Research Board and National Research Council 2005, Reeves et al. 2008; Denoël et al. 2010).

Early surveys of water clarity and total phosphorus (TP) levels indicated generally oligotrophic[2] conditions but showed some indications of shoreline deterioration (e.g. thick algal mats), notably in the more developed southern end of the lake. Initial modelling categorised Leonard Lake as '*above the threshold*[3] *level of enrichment with a moderate sensitivity to development capacity*, and over the past few decades, the lake has been monitored by several agencies (mostly at one or a few offshore sites), the Ontario Ministry of Environment and Climate Change (MOECC), the Muskoka Lakes Association (MLA), the District Municipality of Muskoka (DMM) and the Leonard Lake Stakeholders Association (LLSA). These have generated several datasets, based on different sampling regimes and analytical labs. Overall, these data show generally similar levels of TP and water quality, but the effectiveness of this multi-agency effort and compatibility of these data has not been rigorously assessed.

Since 1971, developed lots on Leonard Lake have more than doubled to 167. Most of these (91%) are located on thin soils, the majority (85%) are 30 m or less from the shore, and a third are built on moderate to steep slopes (Fig. S-2; MWC 2015; Nurnberg 2017). The highest density of properties occurs in the southwest region of the lake. A detailed shoreline survey in 2015 reported that approximately 30% of these properties were 'ornamental' and/or showed erosion, shoreline development (e.g. retaining walls, docks etc.) and lawns. The majority of properties had shorelines with emergent, floating, or submergent aquatic vegetation (MWC 2015).

Based on the geology and topography of the shoreline and catchment, an early study concluded that the lake was largely unsuited for cottage development with subsurface septic systems (OWRC 1971). Nevertheless, all shoreline properties rely on septic wastewater systems of varying age and construction. A 2008 survey conducted by The Township of Muskoka Lakes was unable to determine whether these systems were working properly - hence their contribution to nutrient loads is unknown and are rarely detected by typical monitoring methods (such are currently used by DMM, MOECC and other agencies in Leonard Lake). Localised seepage of (highly bioavailable) nutrients from septic systems can occur throughout the season into the shallow warmer inshore areas. Typically, the nutrients are taken up rapidly by shoreline aquatic plants or algae and decline significantly with distance away from the shore, becoming undetectable at sites a few meters or more offshore. Septic loading can represent a significant proportion of the total nutrient input to a lake and because it is difficult to detect using conventional methods, recent studies have used chemical tracers such as caffeine, sweeteners etc. (Robertson et al. 2013; Spoelstra et al. 2017).
It has been estimated, for example, that septic systems account for 30% or more of the total phosphorus inputs into some of the northern basins of Lake of the Woods (HESL 2011).

[2] i.e. low level of productivity, high water quality and clarity
[3] modelled baseline Phosphorus (P) levels+50%

Septic influx can promote prolific algal or cyanobacterial[4] growth on the bottom, or as biofilms on stones and aquatic plants in the shallow areas along the shoreline, which can dislodge and form surface scums or remain as bottom growth, often invisible to the casual observer. In some cases, these shoreline algal communities can include toxin producing species (Quiblier et al. 2013). It is of note that thick shoreline growth is often reported in areas of Leonard Lake (see below).

Overall, the combination of its size, morphometry, low flushing rates, bottom O_2 depletion and cottage development mean that Leonard Lake is considered vulnerable to the impacts of current and further development, particularly with the current warming trends in climate (LeBlanc et al. 2008, Callieri et al. 2014, Nurnberg 2017).

Biota

There have been several assessments of the biological communities of the lake over the past few decades. A survey by the Ontario Water Resources Commission (1971) conducted in spring, mid-summer, and fall) reported '*large gelatinous masses of the filamentous green algae Zygnema...in nearshore areas of the southern bay, and to a much lesser extent in shallow areas of the main body of the lake...evidence that conditions of accelerated eutrophy*[5] *are developing in the lake*'. A later report similarly described mats of the related species *Spirogyra*[6] Proliferations of these green algae are often indicative of localised inputs of nutrients with a high ratio of nitrogen (N) to phosphorus (P) - typical, for example, of wastewater inputs. The phytoplankton have been sampled for composition and biomass by the MOECC intermittently between 1970 and 2004, particularly in the late 1980s[7]. Analyses were carried out on composite samples from a depth-integrated sample or combined from individual samples collected over the season in each year and were generally not resolved to species level; nevertheless, they provide a valuable baseline series for comparison with more recent years.

Overall, the MOECC phytoplankton samples showed a predominance of colony- and chain-forming chrysophyte flagellates ('golden brown algae'; *Chrysophaerella longispina, Synura, Dinobryon, Uroglena, Mallomonas*), diatoms (*Asterionella formosa, Tabellaria fenestrata,*

[4] Traditionally named '**blue-green algae'**, cyanobacteria are bacteria (not *algae*, which evolved from cyanobacteria and have more complex cell structure and reproduction). They are widely distributed in aquatic and terrestrial systems and in many cases, are important and beneficial components of the foodweb; however, some Cyanobacteria can produce noxious and sometimes toxic **Harmful Algal Blooms (HABs),** which are increasingly a concern. The term 'blue-green' is derived from their pigment, **phycocyanin** (PC) which is commonly used in monitoring to detect their presence in water but is not necessarily diagnostic. PC is often masked by other cell pigments and these species range in colour e.g. blue-green, grass green, yellow-green, pink, black.

[5] **Eutrophy:** advanced productivity (e.g. manifested by algal blooms) as a result of high nutrient inputs

[6] 10 Both of these non-toxic algae belong to the order **Zygnematales** along with other related filamentous 'green' algae and the desmids, reclassified recently under the phylum **Charophyta**, which are closely related to the **Chlorophyta** ('green algae') and land plants; see Guiry (2013). For simplicity, in this report the Charophyta are included in the **Chlorophyta** (i.e. their original taxonomic grouping) in the discussion and graphs.

[7] Raw spreadsheet data obtained from Claire Holeton, MOECC, 2017

Cyclotella sp., *Synedra* sp.) and unicellular dinoflagellates (*Peridinium*). Other groups were present at low abundance and consisted of green algae and desmids (*Botryococcus, Staurastrum, Chlamydomonas, Quadrigula, Gloeocystis, Kirchneriella*; *Dictyosphaerium pulchellum*, Haptophytes (*Chrysochromulina parva*) and small-celled cryptophyte nanoflagellates (*Cryptomonas, Plagioselmis* (formerly called *Rhodomonas), Chroomonas, Katablepharis, Cryptaulax*). A number of these taxa (notably *Chrysophaerella, Dinobryon, Uroglena, Chrysochromulina, Katablepharis, Cryptaulax)* are mixotrophs or heterotrophs (i.e. lack chlorophyll a), and capable of using organic material or ingesting bacteria as a supplemental source energy and nutrients, allowing them to grow at low nutrient or light levels and exploit deep layers of bacteria associated with degrading organic detritus settling out from the surface. This serves to recycle nutrients directly back into the foodweb as part of the 'microbial loop', an important mechanism which facilitates productivity in oligotrophic lakes. It can also provide these algae with a competitive advantage when inorganic nutrient supplies, on which most algae depend, are in low supply, and can enable the development of deep chlorophyll maxima (DCMs), or even dense blooms of these mixotrophic taxa (many of which have a strong fishy-rancid odour; (Watson et al. 2001).

Cyanobacteria were present in low abundance in all MOECC samples, largely represented by Chroococcales and colonial Synechococcales (*Aphanothece, Chroococcus, Dactylococcopsis, Rhabdoderma, Coelosphaerium, Gomphosphaeria* and *Merismopedia*). The toxin-producing genus *Microcystis* was not detected. 'Nuisance' filamentous cyanobacteria were rare, but it is of note that the bloom forming N_2-fixer *Anabaena* (now reclassified as *Dolichospermum*) was not reported until the late 1980s, when it was present in very low abundance.

Zooplankton were surveyed in the 1980s by the MOECC, which reported a community dominated by species of *Daphnia* (*D. ambigua, D. catawba, D. pulex*), *Eubosmina tubicen*, *Leptodaphnia minutus*, calanoid copepods and *Holopedium glacialis* (Table S-3). The invasive spiny waterflea (*Bythotrephes longimanus*) was first recorded in Leonard Lake in 2001 (MNR 2010); this species has invaded many North American lakes including the Great Lakes where it has had serious impacts on the aquatic foodweb. It is inedible to many natural predators due to its long abdominal barbed spine, and preys on smaller keystone zooplankton (Barbiero and Tuchman 2004).

Aquatic benthic invertebrate surveys between 2004 and 2014 show little evidence of environmental impacts on these organisms; long term data indicate a diverse, stable community composition aligned well with the Muskoka average, with a high species richness and percentage of gatherers/shredders and low fractions of chironomids and predators (DMM 2015 datasheet; Table S-4)

A provincial (MNR) survey in 2001 reported that the fish community was dominated by lake whitefish in the deeper areas, and supports a 'marginal' walleye population (stocked between

1940-1960s); other species include burbot, smallmouth bass (introduced in 1939), brown bullhead, yellow perch, lake whitefish, pearl dace, golden shiner and pumpkinseed. The lake is stocked every two years with rainbow trout, which are not well supported by the low levels of productivity of the lake and are targeted by sports fishermen (MNR 2010).

Long-term monitoring programmes

Leonard Lake is one of the 26 lakes monitored at spring overturn and in early fall under the MOECC Lakeshore Capacity and Acid Precipitation programmes, and has been sampled intermittently between 1979 – 1998, and on a yearly basis since 1998. Spring profiles for dissolved oxygen (DO) and water clarity (secchi disk depth, SD) and a single depth-composite water sample[8] are collected at the deepest site as '*representative the entire lake'*,[9] although the complex morphometry of the lake can produce significant local differences in water quality, particularly in sheltered inshore areas (below). The water sample is filtered through an 80µm mesh "*to remove plankton and particulate matter*" - which likely also removes large phytoplankton typically present in this lake in spring, such as chain-forming diatoms and colonial chrysophytes (see below). This sample is analysed for major water quality parameters and chlorophyll a (chl-a)[10].

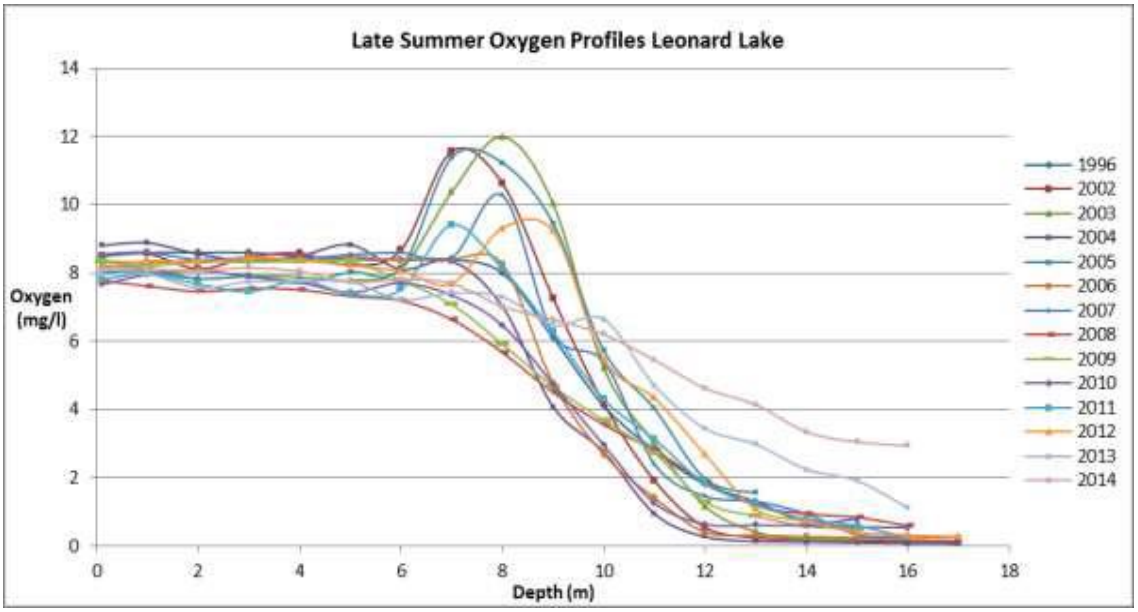

Fig 3. Late summer DO profiles measured at the central monitoring site in Leonard Lake showing deep maxima in some years; from Ingram and Peterson (2015)

While the status of the lake has been largely assessed from the single spring water samples, DO and temperature profiles were taken at this site up to seven times during the open water season in

[8] from odd-numbered depths, through a hose, using a peristaltic pump
[9] MOECC 2015
[10] **chl-a** is a common measure of the **total** abundance of the algal community; it includes all chlorophyll-containing species of algae and cyanobacteria

the 1980-90s, more recently, this has been reduced to a bi-annual frequency (Fig S-3). These data show that thermal stratification is established at the deep site each year, often by early summer, with midsummer surface temperatures between ~16-24ºC. No long-term trends in surface temperatures are apparent.

DO profiles collected at this site often show a peak at variable depths below the surface layer, indicative of deep chlorophyll maxima, associated with aggregations of depth-regulating algae at the 'thermal plate' between the upper and lower lake strata where light and nutrient levels are optimal. Historical data indicate that these DCMs are formed at different times during the season and migrate vertically; in some years they are more pronounced than others (e.g. Fig. 3).

Oxygen profiles also show a significant decrease towards the sediment surface which in some years approaches anoxic or hypoxic levels i.e. 0-2 mg/L.[11] The severity and depth coverage of the O_2 depleted zone varies among years, but generally increases over the season (Fig. 3). This has potential implications for internal loading i.e. nutrient (P, N) release from anoxic sediment surface (e.g. Nurnberg 2017). Despite this, however, Leonard Lake was not included in the 39 'Candidate Anoxic Lakes' that were identified in the recent HESL (2016) report and sampled for internal loading.

Internal loading is often difficult to assess using conventional sampling efforts. In many waterbodies which develop anoxic or hypoxic zones, this process is not necessarily manifested as massive increases in hypolimnetic P and N such as is seen annually, for example, in Sturgeon Bay (Georgian Bay). Nutrients released by anoxic sediment are often dissipated with distance above the bottom, and not detected by sampling efforts which typically collect water at least 1m above the bottom to minimise sediment disturbance. Nutrients are released from anoxic sediments in a highly available form (as phosphate, and ammonia) and are rapidly taken up by bacteria and algae, in some cases stimulating surface blooms, DCMs or thick layers of benthic algae. Two-thirds of the 39 anoxic Muskoka lakes identified in the HESL (2016) report, for example, showed no significant increase in bottom P samples compared to surface levels, and further sampling and assessment was recommended.

Other processes that can directly or indirectly affect the way in which internal loading is manifested include:

- Bottom anoxia and nutrient release can occur on an intermittent, diurnal basis – peaking at night when benthic photosynthetic O_2 generation is absent.
- direct resuspension of oxic or anoxic sediments in shallow basins, releasing interstitial or particle-bound P and N. In large windswept shallow lakes (e.g. Lake Erie, Lake Winnipeg)

[11] **Anoxia** is defined as 0 mg/L DO; **hypoxia** (< 2 mg/L DO) is considered stressful for all aquatic fauna, while concentrations <4 mg/L are stressful for fish (Hawley et al. 2006)

sediment resuspension by wind, waves etc. can result in a significant internal loading (e.g. Matisoff et al. 2017).

- Recreational boats cause sediment resuspension, increasing nutrients and suspended particles in the water, and also have numerous other negative impacts, from exhaust, fuel spillage and hydrocarbon pollutants, propeller contact, induced turbulence and waves, noise, sediment resuspension, disturbance of fish and wildlife, destruction of aquatic plants, and shoreline erosion (Yousef et al. 1980, Asplund 2000, Anthony and Downing 2003, White 2007).
- Nutrients can be recycled into the open water from sediments through bioturbation by aquatic organisms (including bottom dwelling fish like carp), or by uprooting/harvesting aquatic plants which can also uptake nutrients though their roots and release these into the open water during fall/winter die back (Breukelaar et. al. 1994, Søndergaard et al. 2003).
- Nutrients can be translocated by algae, which uptake P directly from the sediment or from nutrient-rich lower water column layers and then transport it in their cells to the surface (e.g. the bottom-growing cyanobacteria *Gloeotrichia*, or vertically migrating /buoyancy regulating

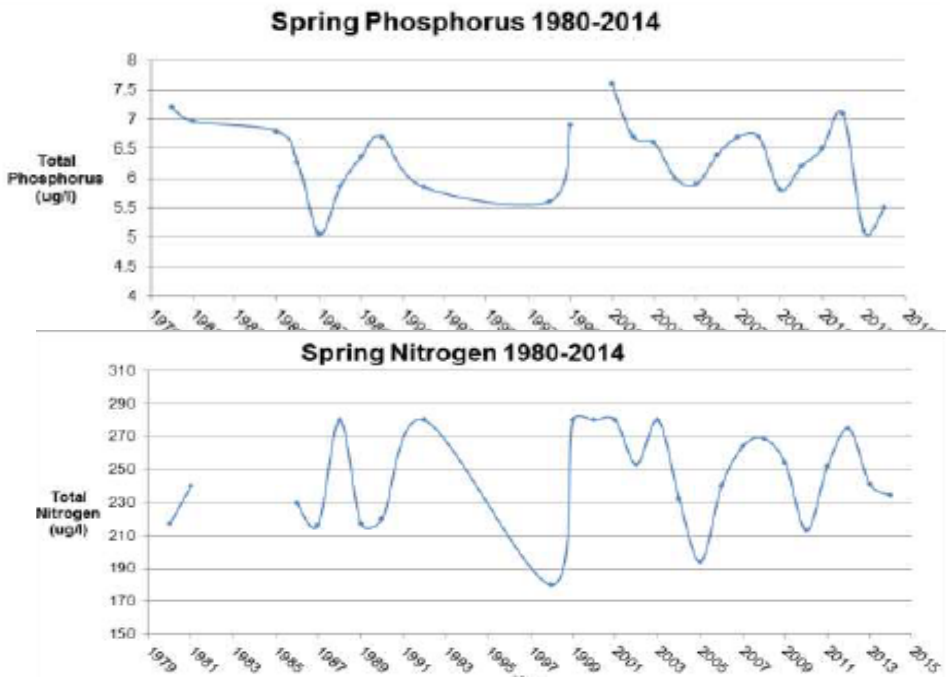

Fig 4. Long term trend in spring total P and total N in depth composite samples at the central monitoring site in Leonard Lake; from Ingram and Peterson 2015

flagellates (e.g. *Dinobryon, Uroglena*) and HAB forming cyanobacteria such as *Dolichospermum*, *Aphanizomenon*, *Planktothrix*).

Recent work using more advanced methods (peepers, geochemical modelling, stable isotopes) has demonstrated that these processes can account for a significant fraction of the nutrient budget of a lake (Dittrich et al. 2013, Paytan et al. 2017, Matisoff et al. 2017). It is of note that with increasing

eutrophy, the capacity of the sediments to 'sink' P appears to be permanently diminished as a result of geochemical changes in the sediments (Rothe 2015).

The MOECC report a gradual decrease in spring TP in Shield lakes, but data for Leonard Lake show variable levels and no significant long-term trend, as was verified by a recent analysis of the Muskoka lake data (HESL 2016). Between 1979 and 2015, TP ranged between ~ 5 - 7.5 µg/L (Fig 4), characteristic of oligotrophic conditions in this ecoregion (CCME 2006) and of median TP concentrations across the 1421 lakes monitored under the Lake Partnership Programme (LPP)[12]. However, it is important to note that after 2002, LPP samples were analysed at the Dorset Environmental Science Centre and these more recent data are ~10x more precise; samples analysed prior to this have a high associated error and should not be used to assess long term trends (A. DeSellas, LPP coordinator, personal communication 2017). This highlights the issue with data compatibility and the potential error introduced by differences in analytical protocols.

Spring total Nitrogen (TN) has been similarly low and variable, ranging between ~180-280 µg/L (Fig 4; Tables S-1, S-2) and showing no clear long-term trend. The data indicate an average spring TN:TP of ~16 (molar ratio), indicating that P, not N, is the primary nutrient limiting productivity at ice out.

Management and development capacity

A series of reports assessed nutrient levels across a range of Muskoka and Ontario lakes and developed management targets, models and strategies (CCME 2006, Gartner Lee 2005, HESL 2016). The CCME study identified distinct spatial patterns in TP in lakes in the three Ontario Ecozones[13] and assessed the primary factors contributing to these patterns (CCME 2006). These included

- Catchment bedrock and surficial geology.
- Lake and catchment size, shape and topography, vegetation
- Lake residence time (flushing rate)
- Susceptibility to bottom anoxia
- Density, type of dwellings (cottages, camp grounds, hotels etc.)
- Wetland coverage in catchment
- Wastewater and septic systems (design, drainage bed composition, distance from shore, age, usage / capacity and nutrient contribution)

Given the unique nature of every lake it was recommended that they are evaluated for these characteristics on an individual basis to assess development capacity and develop management

[12] the LPP data represent a separate sampling programme based on volunteer collection of subsurface ('dip') samples where there was often high sampling error involved. See Supplementary material for 2002-2015 LPP data for Leonard Lake

[13] Mixed Wood Plains, Boreal Shield, and Hudson Plains; see the following link: https://www.ccme.ca/files/Resources/water/water_quality/phosphorous_ecoregion_rpt_1.0_e.pdf

strategies, particularly lakes that are in the above-threshold[14], moderate-to-highly sensitive[15] categories; the latter group should be assessed further for soil composition, depth and P adsorption ratio (CCME 2006, HESL 2016).

Risk analysis should consider these factors, and the criteria and thresholds used to define risk and management targets. The quality of the data used to define and validate management decisions should be examined critically, and collection/analytical methods optimised. With the current scenario of climate change, for example, sampling protocols (timing, frequency, sampling/analytical methods, spatial and depth coverage) should be adaptively managed; with earlier spring thaw, rigid field schedules are often out of sync with loading, runoff and ice-free seasonal lake events.

TP measures are simple and cost effective, but taken alone they do not provide an adequate gauge of lake status, which is best assessed using several indicators (e.g. Carlson 1977; 1981, Eimers et al. 2009). Traditionally, P has been shown as the primary limiting nutrient in most North temperate lakes. It is present in a variety of organic and inorganic forms which undergo complex transformations, affecting its bioavailability (e.g. Bostrom et al. 1988, Wetzel 2001). These processes are affected by the chemistry and temporal-spatial patterns of P loading (external and internal) and the physiochemical and biological characteristics of individual waterbodies. Total P thus represents a variety of dissolved and particulate forms, which vary seasonally and spatially and are affected by basin morphometry, climate and catchment size/development/ and biological activity (e.g. Clarke et al. 2010 and many others). Seasonal averages of intermittently spaced TP measures are thus unlikely to provide a robust assessment of lake-wide nutrient levels and availability across the season.

TP data alone cannot adequately capture potential issues in water quality related to harmful algal blooms (HABs) and/or those dominated by cyanobacteria (cHABs). Many of these blooms occur in shoreline areas where there is greatest risk of public exposure. As noted above, TP does not measure bioavailability - the degree to which it will stimulate biological activity and risk of noxious and/or toxic HABs/cHABs. For example, the recent and dramatic increase in toxic cHABs in the west basin of Lake Erie have occurred during a period where there was no significant change in <u>total</u> P loading or in-lake concentrations, and is attributed to an increase in the %bioavailable P in this loading, and changes in the timing of these loads, which are often decoupled in time from the apex of the bloom events (Stumpf et al. 2016, Watson et al. 2016a). Increasing evidence is also pointing to the important role of other factors in controlling bloom development – notably nitrogen (N) and mixing (water column stability) (O'Neil et al. 2012, Orihel at al. 2013, Watson et al. 2016b).

[14] **Threshold defined as modelled baseline P levels+50%,** as determined for each lake
[15] Sensitivity defined by **capacity to accommodate further development** (i.e. P influx)

TP measures can often lack precision and/or accuracy, due to sampling and analytical errors. This is important, since small changes in P supply (e.g. in the order of µMol) can have significant effects on algal growth. Differences in analytical methods can produce significant discrepancies among data generated by different labs, and inter-lab comparisons should be conducted if multiple labs are used for analysis of the same parameters. Similarly, sample collection can introduce error through contamination of equipment, collection bottles, surface debris, sediment disturbance etc. As a result, measures of TP often have large coefficients of variation – in Muskoka lakes, this error ranges between 30-60% (e.g. Gartner Lee 2005, 2008). Mid-lake TP levels can differ significantly from those in inshore areas due to currents, wind and wave action, reduced flushing, warmer temperatures, shoreline inputs of nutrients and other material (anthropogenic and natural), groundwater influx, sediment exchange and bioturbation[16]. This heterogeneity in nutrient distribution is particularly an issue in lakes with low flushing rates, complex morphometry – e.g. multiple basins, islands, wetlands, embayments, deep and shallow areas - and a vulnerability to bottom anoxia. It is also of concern for those lakes with shoreline properties with septic systems that are improperly installed or maintained, or under capacity (e.g. properties that have been enlarged and converted into year-round residences). This introduces considerable uncertainty into modelling predictions and the interpretation of long term trends.

TP is not a reliable predictor of chl-a; in many cases there is a poor and/or highly variable and non-linear relationship between these measures (e.g. Carlson 1984, Watson et al. 1992); for example, a poor correlation between TP and chl-a is reported for Muskoka and other regions of Ontario (Gartner Lee 2005). Despite this, long-term monitoring programmes have relied largely on TP as the primary measure of lake status in Muskoka, and other indicators have been overlooked, particularly over the past few decades. The routine measurement of chl-a in Muskoka lakes was discontinued several decades ago, although it is an important indicator of eutrophication and trophic status (e.g. Carlson 1981) which is widely used in many national, international and local lake management programmes (e.g. SOLEC 2016; USEPA, 2017).

Climate change and other stressors related to human activity can profoundly alter a lake's nutrient balance and resilience to development, affecting seasonal ice coverage, runoff, stratification patterns, nutrient input and retention, water chemistry and extent of noxious algal growth (e.g., Hadley et al. 2013, Persaud et al. 2014, Winter et al. 2011, Watson et al. 2016a,b). This can increase the number, geographical range and diversity of lakes that are at risk - and the monitoring efforts required - and necessitate a re-evaluation of earlier management criteria and targets focussed on TP. Climate-related changes in water levels and runoff, for example, are key factors in the recent increases in cHABs in nutrient-poor (oligotrophic) lakes (e.g. LeBlanc et al. 2008, Callieri et al. 2014).

[16] sediment disturbance by living organisms.

The DMM has traditionally managed the water quality and recreational development of lakes using a model based on the provincial Lakeshore Capacity Model (LCM). This model was developed and validated using data not necessarily representative of the Muskoka region, and defined a lake's capacity for recreational development using catchment characteristics, modelled TP levels and lake morphometrics (Gartner Lee 2005). This approach defined a single ("Over Threshold") category to calculate development capacity and "Low", "Moderate" and "High" Sensitivity ratings to P loads to manage future development and protect water quality. Using this approach, Leonard Lake was classified as *above the threshold*[17] *level of enrichment with a moderate sensitivity to development capacit*y i.e. having some capacity to accommodate increased P inputs "without a significant decrease in water quality". Monitoring data, however, showed considerable variance between observed and modelled P levels, which thus could not be reliably used to describe development capacity.

The DMM has recently proposed the OP 45 Amendment, based on a Revised Water Quality Model and Lake System Health Program (HESL 2016). This Amendment proposes to revise the earlier lake classifications and development criteria and claims to thereby address some of the limitations of this TP-based model, which did not consider the multiple other stressors on these systems. Based on a more 'holistic' approach, it re-defines water quality management targets and commercial development criteria to remove some of the focus on TP. Yet although a multi-year study in the Muskoka watershed concluded that multiple indicators should be used (Eimers 2016), the OP 45 Amendment proposes three simple metrics to assess a lake's sensitivity to development and risk of 'blue-green algal' blooms (aka cHABs), two of which are based on TP data:

- A long-term statistically significant increasing trend in TP concentration demonstrated by at least five (5) sample measurements starting in 2001 or thereabouts;
- A long-term TP concentration > 20 µg/L[18], demonstrated by the average of five (5) most recent spring overturn TP sample measurements taken within the last ten (10) years
- A blue-green algal (cyanobacteria) bloom *confirmed by the province or health unit* and comprised of cyanobacteria species.

These criteria risk excluding lakes with an elevated sensitivity to development and associated impacts (e.g. increased inputs of nutrients, suspended solids, shoreline degradation, habitat disturbance etc.) for a number of reasons:

- As noted in HESL (2016) "*The estimate of total phosphorus loading to a lake becomes increasingly uncertain as development increases because of the uncertainty associated with the mobility of phosphorus from septic systems"*
- Significant water quality degradation and algal blooms can accompany TP levels below 20µg/L, a trend that is increasing with climate change-induced fluctuations in flushing and lake levels (e.g. LeBlanc et al. 2008, Callieri et al. 2014, Salmaso et al. 2015).

[17] modelled baseline P levels+50%
[18] interim provincial water quality objectives for TP to protect against algal/cyanobacterial blooms

- The target TP level is assessed using DMM data largely collected at ice-out, isothermal[19] conditions, when the impacts of cottages, recreational activities, boats, severe storms etc. are low. During the summer period, these activities increase, and have a very different effect on the lake; the response to nutrient inputs of nuisance algae/ cyanobacteria is enhanced by warm temperatures, increased daylength and water column stability.
- The low frequency and seasonal/spatial coverage represented in the current monitoring programme is, in many cases, too course-grained to detect long term trends in TP, particularly in morphometrically complex lakes.
- The third criterion is focussed on cyanobacteria, some of which can produce toxins. However:
  -Toxicity cannot be determined from field inspection or microscope examination, and should be verified by lab tests, although commercial kits can be used to screen for toxicity on site (Watson et al. 2017);
  -Public awareness and reporting of algal blooms has escalated in the past decade, and often exceeds the lab and field capacity for timely sampling and analysis of these events - which can form and disperse rapidly[20];
  -Many cyanobacteria blooms are non-toxic, but can nevertheless cause significant socioeconomic harm (taste-odour, shoreline fouling, impaired recreational areas, impacts to food-webs and fisheries etc.);
  -Surface blooms are often formed from inconspicuous or 'hidden' populations dispersed through the water column or present as DCMs during calm conditions. These can persist undetected in the water column for some time and may or may not aggregate at the surface; thus are often not detected or reported. It is important to monitor the species and their abundances during the mid-late summer;
  -Benthic [21] mats of algae and cyanobacteria are rarely sampled in most monitoring programmes, but are also a potential 'hidden' source of toxins, and/or noxious odours and shoreline fouling and can significantly impair habitat and spawning areas for fish and other organisms (Quiblier et al. 2013).
  -Other non-cyanobacterial species can also develop HABs. These include *Cladophora, Spirogyra* and other attached algae, which foul beaches and shorelines with rotting material, increasing bacterial levels and putrid odours in these areas and decreasing property value. Golden-brown algae (Chrysophyta), dinoflagellates and diatoms can produce noxious

[19] Fully mixed water column

[20] e.g. Leonard Lake Association (LLSA) made 3 calls between Sept 14-26 2017 to the Spills Action Centre to report a scum at several inshore sites. At the same time, LLA collected samples of this material which were preserved with Lugols and sent for microscopic analysis by ATEI, Winnipeg (H. Kling). This showed that one site in particular was dominated by cyanobacteria (>99% *Dolichospermum (Anabaena) lemmermannii* (see Fig S-), a known toxin producer in other lakes). MOECC sampled a single site on Sept 15 (when the bloom had disappeared); this sample was not found to contain a bloom.

[21] Bottom-dwelling

blooms and taste-odour, impacting recreational and drinking water quality (e.g. Watson and Molot 2013; Watson et al. 2001, 2016b).

Leonard Lake Association study, 2017

Rationale

Anecdotal reports of increased surface algal blooms in Leonard Lake over the past few years indicated a decline in water quality and a need to continue to monitor the lake and restrict further development. None of the blooms was sampled or identified and there was increasing concern with the risk of cyanobacteria. Long-term data at the offshore monitoring sites show generally low nutrient and chl-a levels, but no detailed survey of inshore sites had been made. Furthermore, there is serious concern with the revised classification of Leonard Lake and proposed OP 45 Amendment, which would allow less constraint on lot development. A recent in-depth evaluation of the catchment and lake morphometrics and hydrology and the (DO, temperature) profile data from the deep monitoring site highlighted the potential for internal loading and need to more fully characterise this issue (Nurnberg 2017). As noted earlier, DO profiles show a high vulnerability to bottom oxygen depletion and indicate the intermittent presence of deep-living algal maxima of unknown species composition. In many lakes these deep maxima are composed of chrysophytes and other flagellates which are of high nutritional value to zooplankton, but some lakes in the region (spanning a range of nutrient levels) show annual development of cyanobacteria-dominated deep maxima (e.g. Lake Ontario, Lake 227 in ELA, Twelve Mile Bay; M. Verschoor, S. Watson, unpublished data).

Methods

To address these issues, during 2017, the Leonard Lake Stakeholders Association undertook a three-pronged investigation of the lake, with a focus on the present and possible future occurrence of algae blooms in the lake. Samples were collected at sites in offshore and inshore areas (Figs. S-4, S-5; Table S-5), some on several occasions during the open water period. The purpose of this work was to:

i) characterise spatial and temporal range in water quality, major nutrients (P, N) and algae/cyanobacteria

ii) assess bottom anoxia across the lake and evidence of internal loading

iii) sample and analyse water quality and algal species composition in any deep chlorophyll maxima detected during sampling

iv) sample and characterize the prevalence of cyanobacteria in any algal blooms reported around the lake.

At each site, a depth profile for temperature, dissolved oxygen and chl-a fluorescence was collected at 1m increments from the surface down to 1 m above the bottom using a YSI© EXO1 Sonde. Secchi depth and surface temperature were also recorded. Individual samples were collected at specific depths for water chemistry using a horizontal sampler at 1m, 1m above the bottom, and based on the profile data, at the depth of any DCM, or if none was present, at 0.5 m above the

thermocline[22]. Subsamples were filtered directly in the field into sample tubes using a syringe filter and 0.45µm membrane filters for dissolved metals and inorganic N analysis (nitrate/nitrite, ammonia); N samples were frozen until analysis. Subsamples were also processed for other water quality measures (TP, total dissolved P, chl-a) at the shore-based lab. These were shipped overnight to the Biogeochemical Analytical Service Laboratory (BASL), Edmonton AB or stored until analysis at Trent University Water Quality Centre (total dissolved metals). Method descriptions and minimum detection and quantification levels for the analyses are given in Table S-6.

Depth-integrated (composite) samples were collected over the season at several offshore monitoring sites, mainly stations 36 and NDH (Fig. S-4). On most occasions, this was carried out using the horizontal sampler at 1m intervals down to a depth corresponding to the approximate photic zone[23] (estimated as twice the Secchi depth). These individual samples were then combined into a composite sample which was preserved for phytoplankton analysis at ATEI, Winnipeg Manitoba using the standard Utermöhl technique (Findlay and Kling 1998). As the horizontal sampler was not available until mid-season (July), earlier samples were collected using different protocols: in May, a surface sample was collected manually as an 'elbow' depth dip (~0.5m), while in June, a tube sampler was used to collect the integrated sample.

At selected sites, plankton was concentrated using replicate (4) hauls with a 20 µm 'Student' Nitex© plankton net over a depth of ~5m. These samples were sent as both unpreserved and Lugol's preserved samples to ATEI for quantitative analysis of the major species present (Fig. S-4; Table S-5). In response to several reports of surface blooms in shoreline areas in mid September, unpreserved and preserved net samples were also collected between September 14-17th at five sites (QL 6,7,8,9,10; Fig. S-4), together with a composite sample at the central monitoring site (station 36), to assess the species composition of these blooms and any potential risk to the residents.

Results and Discussion

Profiles

Depth profiles taken between Aug 21-23, 2017 showed stratification at all 4 offshore sites. Surface temperatures were similar at all sites (22.6 ^{o}C) except station 36, where it was marginally cooler (21.5 ^{o}C) (Figs S-4, S-5). The depth of the mixed layer (epilimnion) extended past the Secchi depth (which showed good water transparency across the lake, ranging between 3.2-3.7 m), down to a depth of ~4.5-5 m.

Dissolved oxygen profiles showed significant declines with depth at all four sites, with concentrations decreasing to <4 mg/L at the bottom of the water column (1m above the sediment

[22] Where the water column is thermally stratified; the **thermocline** is defined as the depth range covering the abrupt decline in water temperature, marking boundary between the warmer mixed surface layer (**epilimnion**) and cooler deep water **(hypolimnion**)

[23] [Theoretical] water column depth with sufficient light to support photosynthesis

surface) and reaching anoxic conditions at the deep site in the north basin (NDH) and site 2 in the south (Figs S-4, S-5). MDL: minimum detection level; QL: quantification level

Table 1 Dissolved and total P and N, and extracted chl-a at the four sampling sites, August 2017

Site	Depth (m)	Date	Secchi (m)	NH_3 (µg/L)	NO_2+ NO_3 (µg/L)	TDN (µg/L)	TN (µg/L)	TP (µg/L)	TDP (µg/L)	Chl-a (µg/L)
NDH	1	21-Aug-17	3.5	53	<MDL	246	248	29	17	2.2
	3.5			20	8	220	266	16	7	2.7
	15			595	130	320	339	8	*7*	1.0
32	1	22-Aug-17	3.7	5	3	223	247	17	5	3.7
	4.5			<MDL	129	240	262	7	11	3.7
	7			37	20	203	227	7	5	3.0
2	1	22-Aug-17	3.2	39	15	215	273	8	5	4.3
	3.5			51	4	218	240	8	8	4.2
	7			62	7	242	319	16	11	28.7
36	1	23-Aug-17	3.2	17	120	254	236	17	5	4.8
	4.5			66	8	225	247	7	4	5.1
	11.5			68	71	283	286	6	3	1.5
MDL				3	2	7	7	1.4	1.8	0.2
QL				8.2	5.9	7	23	3.1	4.9	N/A

The bottom anoxia at the shallow south site 2 was unexpected, and did not appear to reflect sediment disturbance by the probe as the decline in DO began at 4m, well above the sediment surface. This was the only site where dissolved and total P and ammonia increased in the B-1m sample (Table 1), suggesting internal loading[24]. This site also showed a significant increase in conductivity with depth, possibly suggesting an intrusion of groundwater or shoreline seepage. However, as noted above, anoxic sediment release is difficult to detect from a boat, particularly where conditions are choppy and sampling close to the sediments is necessarily conservative.

[24] However, inconsistencies between low chl-a (2.2 µg/L) and high total and dissolved nutrient data (e.g. TP, TDP=29, 17 µg/L respectively) in surface samples from NDH suggest a mix-up between 1m and B-1m nutrient samples at this site but this cannot be verified.

Unlike earlier studies, there was no clear evidence of a DCM in the DO profiles (Fig. S-5), although there was a slight increase in chl-a fluorescence towards the middle of the water column at most sites, with no consistent alignment with the temperature or DO profiles. There was, however, no corresponding peak in nutrient levels at these depths. Phycocyanin (PC) fluorescence was very low and increased slightly towards the bottom at all sites. This could be interpreted as an increase in cyanobacteria with depth; however, it is more likely that these profiles reflect an increase in DOC towards the bottom, as this material produces background fluorescence which can interfere with PC readings.

Nutrients and chl-a

Summer (August)

TP ranged between 6-29 µg/L across all samples and were higher in the surface than the deeper samples (except at site 2, as noted; Table 1). The data showed considerable spatial variance, which was unrelated to the maximum depth or chl-a at each site. Overall, TP levels were significantly higher than those measured in other monitoring programmes (e.g. Tables 1, S-1, S-2), which may reflect sampling/analytical methods or genuine differences, possibly related to season (most long-term monitoring programmes are based on spring, mixed conditions). This discrepancy should be followed up with further sampling and rigorous interlab and interagency comparisons.

Total dissolved P accounted for 30-100% of the TP, with the %dissolved fraction generally lower at the surface where most P was present in plankton cells and other particles (Table 1). With the exception of the bottom anoxic layer at the deep northern site (NDH), dissolved inorganic N (i.e. NO_3, NH_4) was low and most of the dissolved fraction present as organic N. This may represent a variety of different organic compounds including urea, amino acids, peptides etc., some of which are readily assimilated by some algae and cyanobacteria (Donald et al. 2013). TN:TP (molar) ratios were almost consistently >16, as also seen with previous monitoring data (discussed above), indicating that N is not the primary nutrient limiting algal growth and productivity in Leonard Lake.

Extracted chl-a ranged between 2.2 - 4.8 µg/L in the surface waters, with higher levels at the south and central stations (sites 2 and 36). It is of particular note that the lowest chl-a levels were measured at the deep site in the northern end of the lake (Table 1), which serves as the basis for much of the long-term monitoring by the provincial and district agencies. This suggests that these long-term data underrepresent the level of productivity in the lake, and demonstrates that future monitoring sites should be carefully selected. The shallowest site (site 2) also showed significantly higher chl-a (28.7 µg/L) in the bottom sample (not evidenced in the fluorescence profile or plankton sample collected at 7m depth; see below), suggesting a layer of live algal cells settled out from the plankton, or an actively growing benthic population. Given the shallow nature of this area of the lake, benthic algal growth is highly probable, and could represent a significant contribution to the overall productivity of the lake.

Table 2. Dissolved and total P and N, and extracted chl-a in the north and south basin sites NDH and station 2, October 17th, 2017

Statistic*	site	depth (m)	NH_3 (µg/L)	NO_2+ NO_3 (µg/L)	TDN (µg/L)	TN (µg/L)	TKN (µg/L)	TP (µg/L)	TDP (µg/L)	Chl-a (µg/L)
average	NDH	1	<MDL	<MDL	231	280	280	6	2	6.9
STD					*1*	*46*	*46*	*1*	*0*	*0*
average		15	189	2.5	364	365	363	12	3	1.2
STD			*6*	*2*	*9*	*8*	*11*	*1*	*0*	*0*
average	STN 2	1	<MDL	2	245	293	292	6	2	6.0
STD				*1*	*7*	*40*	*41*	*1*	*0*	*0.2*
average		8	178	<MDL	456	447	447	8	3	6.7
STD			*1*		*29*	*22*	*22*	*0*	*0*	*0.30*
MDL			3	2	7	7	7	1.4	1.8	0.2
QL			0.2	5.9	7	23	23	3.1	4.9	N/A

* based on the analysis of duplicate subsamples from the same sample

October

Phosphorus levels were generally lower in the mid- October samples, and close to the long-term averages for this lake (Table 3). At both north and south basin sites, bottom samples showed higher TP levels than surface, particularly at the deeper NDH site. TDP showed little depth-related change, suggesting that the increase was largely in the form of particles, possibly representing settled phytoplankton cells and other organic material. This is consistent with the elevated bottom levels of NH_4 and low concurrent nitrate concentrations at both sites, suggesting mineralization of organic material. DO and temperature profiles were not collected, so the presence of any anoxia or hypoxia and associated internal loading could not be assessed.

Metals

Dissolved metals were generally representative of average levels seen across a range of 28 Canadian lakes (Table 3; M. Verschoor, in prep.) and below Canadian and Ontario Guidelines for the Protection of Aquatic Life, with a few anomalies. The one high aluminium (Al) measure at 3m at site NDH may represent clay contamination at the thermocline, while the high hypolimnetic iron (Fe) values at both sites likely reflect anoxic sediment reduction processes. Copper and cadmium (Cu, Cd) were slightly elevated, particularly in the hypolimnion which may reflect the metal deposits in the local geology. Zinc levels were significantly elevated relative to

Table 3. Total dissolved metals (mean ±%RSD) at north and south sites in Leonard Lake (LL), August 2017; values highlighted where they exceed Canadian Water Quality Guidelines for the Protection of Aquatic Life (CWQG) or Provincial Water Quality Objectives (PWQO) for the range of alkalinity seen in LL (<75 mg/L $CaCO_3$)

date	21-Aug-17			22-Aug-17				
Station	LLNDH			STN2				
depth	1	3.5	15	1	3.5	7	CWQG	PWQO
	ppb							
Be	0.01	0.01	0.01	0.01	0.01	0.01		11
%RSD	*5.7*	*12.3*	*16.8*	*20.5*	*5.9*	*12.2*		
B	30.4	15.3	9.1	9.7	10.9	9.4		
%RSD	*1.0*	*3.0*	*4.7*	*0.8*	*1.6*	*4.0*		
Al	17.4	**156.7**	49.9	14.7	18.6	85.9	100	75
%RSD	*2.3*	*5.1*	*0.7*	*1.0*	*1.5*	*2.4*		
Ti	0.3	2.8	0.8	0.3	0.3	1.1		
%RSD	*11.6*	*6.4*	*6.2*	*22.4*	*2.3*	*11.0*		
V	0.1	0.8	0.1	0.1	0.1	0.2		6
%RSD	*3.9*	*2.5*	*2.5*	*6.3*	*5.5*	*4.8*		
Cr	1.4	1.5	1.4	1.3	1.2	1.6	8.9	8.9
%RSD	*5.4*	*2.9*	*1.0*	*1.3*	*1.5*	*1.5*		
Mn	11.5	2.3	446.1	2.7	4.4	910.5		
%RSD	*4.7*	*3.9*	*1.6*	*2.2*	*1.4*	*2.8*		
Fe	21.2	17.2	317.8	22.5	28.0	**1291.1**	300	300
%RSD	*2.2*	*4.2*	*1.1*	*3.3*	*1.1*	*2.1*		
Co	0.1	0.1	0.8	0.0	0.1	**1.2**		0.9
%RSD	*8.9*	*5.9*	*2.3*	*8.9*	*2.0*	*3.6*		
Ni	1.2	1.3	1.4	1.2	1.1	1.6	25	
%RSD	*4.7*	*4.8*	*4.1*	*3.1*	*0.4*	*7.2*		
Cu	0.9	**1.3**	**1.7**	**1.2**	1.0	**1.3**	2	1
%RSD	*6.0*	*6.5*	*0.5*	*7.5*	*3.1*	*5.3*		
Zn	**186.6**	**1584.4**	**52.4**	**37.6**	**154.7**	**132.9**	30	20
%RSD	*2.4*	*2.9*	*1.1*	*2.0*	*3.8*	*3.2*		
As	0.4	0.3	0.4	0.4	0.4	0.7	5	5
%RSD	*12.3*	*3.4*	*9.2*	*14.9*	*11.9*	*7.3*		
Se	0.1	0.1	0.2	0.2	0.1	0.1	100	100
%RSD	*11.4*	*8.7*	*18.7*	*27.6*	*18.0*	*17.2*		
Sr	15.7	17.7	15.5	14.2	14.8	18.9		
%RSD	*2.6*	*5.0*	*2.0*	*2.4*	*1.1*	*2.5*		
Mo	1.5	2.6	1.3	1.1	0.8	0.7	73	40
%RSD	*3.1*	*8.8*	*6.9*	*4.3*	*6.3*	*1.9*		
Ag	0	0.01	0	0	0	0.01	0.25	
%RSD	*29.44*	*4.52*	*9.45*	*38.99*	*29.06*	*26.91*		
Cd	0.01	**0.03**	**0.06**	0.01	0.01	**0.07**	0.017	0.1
%RSD	*13.2*	*14.2*	*8.8*	*26.5*	*2.7*	*4.5*		
Sn	0.1	0.1	0.1	0.1	0.1	0.1		
%RSD	*8.8*	*3.9*	*4.9*	*3.0*	*5.3*	*5.5*		
Sb	0.1	0.1	0.1	0.1	0.1	0.1		
%RSD	*2.2*	*7.8*	*5.8*	*0.6*	*5.6*	*7.6*		
Ba	154.9	116.0	97.3	112.8	126.8	86.3		
%RSD	*1.0*	*4.4*	*1.3*	*1.2*	*2.4*	*2.0*		
Tl	0.0	0.0	0.0	0.0	0.0	0.0	0.8	
%RSD	*14.6*	*10.5*	*15.7*	*27.4*	*41.0*	*18.0*		
Pb	0.1	0.1	0.3	0.1	0.1	0.5	1	1
%RSD	*3.1*	*2.0*	*1.4*	*1.9*	*7.2*	*1.4*		
U	0.0	0.0	0.0	0.0	0.0	0.0	15	
%RSD	*4.8*	*7.7*	*4.4*	*7.9*	*11.6*	*8.7*		

the guidelines, which again is not uncommon in this region where lakes often show Zn levels far exceeding the 30 ppb[25] level with a hypolimnetic gradient in Zn similar to iron and manganese.

Zinc also seems to form a pattern of concentration in the metalimnion towards the end of the season in some lakes, which could represent settling material or bio-accumulation (M. Verschoor, in prep).

Algae

May-June Plankton assemblages

Spring plankton samples from the central site (station 36) showed a mixed community in surface samples, with a marginal increase in Total Algal Biomass (TB) and the abundance of flagellates - chrysophytes and dinoflagellates- between May 28th and June 28th. Overall there was little change between the May and June surface water assemblages, which showed comparably low total biomass (360, 380 µg/L respectively; Fig. 5).

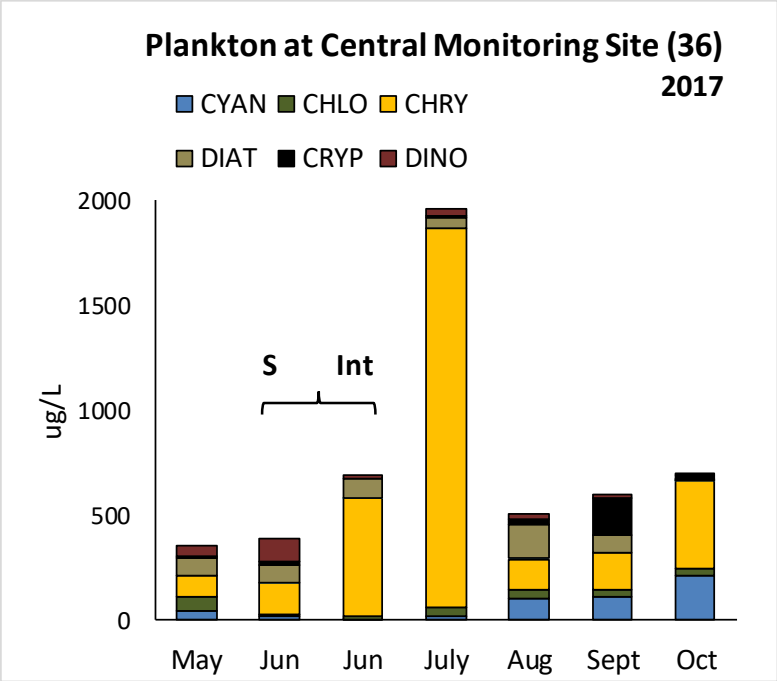

Fig. 5. Seasonal changes in phytoplankton biomass and composition in depth-integrated samples at the central monitoring site (36), Leonard Lake. CYAN=Cyanobacteria; CHLO=Chlorophyta (green algae), CHRY=Chrysophyta, DIAT=diatoms, CRYP=Cryptophyta, DINO=Dinophyta; Surface (S) and Integrated (Int) samples from June included

In May, surface algal biomass showed a fairly even distribution among several taxonomic groups. There was a predominance of diatoms (esp. *Tabellaria fenestrata*, *Lindivia* (formerly called *Cyclotella*) *bodanica* complex), mixotrophic and scaled chrysophytes (notably the mixotroph

[25] i.e. milligrams per litre (mg/L) of water

Uroglena spp., which have been shown to have a high ability to use bacterial grazing as an alternative resource under low light and inorganic nutrient levels; Watson 1999) and other flagellates (e.g. dinoflagellates; *Gymnodinium mirable*) and cryptophytes, *Cryptomonas reflexa, C. marssonii, Plagioselmis nanoplanktica* formerly called *Rhodomonas lacustris*), typical of spring algal assemblages in oligotrophic lakes (e.g. Watson and Kling 2017). The surface June biomass was fairly evenly distributed among three major algal groups that are typical of spring assemblages in softwater oligotrophic lakes, dinoflagellates (*Gymnodinium mirable*), diatoms (*Tabellaria fenestrata, Cyclotella bodanica* complex) and large colonial chrysophytes with a reduced prevalence of mixotrophs (*Synura* sp., *Dinobryon sertularia* and *Chrysosphaerella multispina/ longispina*). The depth-integrated sample collected in June showed a much higher (~2x) biomass than the corresponding 1m surface sample (total algal biomass of 389, 695 µg/L respectively), which likely reflects a deep-living population captured in the composite sample (this was not collected in May). In particular, the integrated sample showed a much higher biomass of large colonial chrysophyte flagellates (*Synura* sp., *Dinobryon sertularia* and *Chrysosphaerella multispina / longispina*).

Cyanobacteria were very minor constituents of both the May and June samples, largely represented by small celled colonial or filamentous picocyanobacteria [26] (*Aphanocapsa delicatissima, Aphanothece minutissima (Syn Anathece minutissima), Cyanodictyon planktonica, Planktolyngbya* sp., *Radiocystis geminate*) that are common in plankton assemblages, particularly in oligotrophic lakes (e.g. Watson and Kling 2017). A very small population of filamentous nitrogen fixers was present in the May surface sample (9 µg/L; *Dolichospermum lemmermanii, D. planktonicum*), but no heterocysts[27] were observed, indicating that N was not limiting at this time. These cyanobacteria were not observed in June, when they may have been present at insufficient abundance to be detected.

July plankton

The composite sample from July (station 36) contained a significantly higher total biomass than the spring samples (1966 µg/L; Fig 5), and was overwhelmingly dominated by colonial chrysophytes (91%TB), notably *Dinobryon sertularia* (70% TB), along with other mixotrophic and scaled chrysophytes *(Dinobryon bavaricum, Synura* cf *splendida, Ochromonas* sp., *Mallomonas caudata, M. tonsurata*). Again, this may have reflected the presence of a significant DCM. The large colonial scaled chrysophyte *Chrysosphaerella* was low in abundance or absent from this and later samples, consistent with its preference for cooler spring conditions. Other algal groups were minor components of the sample biomass, and included green algae (i.e. Chlorophyta; 2%TB; notably colonies of *Botryococcus braunii*), diatoms (2% TB; *Cyclotella. bodanica,*

[26] **Picocyanobacteria** are small celled cyanobacteria (typically <2um in cell diameter) which are abundant in many oligotrophic systems where they are an essential part of the foodweb. They occur singly or in colonies or filaments

[27] **Heterocysts** are specialised cells are produced by these species which have the capacity to fix atmospheric N_2 i.e. convert this to a usable form; this capacity is lacking in algae and most other organisms (except certain bacteria), and provides these species with a competitive advantage when supplies of more bioavailable N are low

Fragilaria sp.) and dinoflagellates (2% TB; *Parvodinium cf pusillum*; *Gymnodinium* sp. *Peridinium* sp.). A similar assemblage of small filamentous and colonial picocyanobacteria was again present at very low abundance (<2% TB); bloom-forming species like *Dolichospermum* were not observed.

Net hauls collected at three inshore sites (QL3, QL4, QL5) showed similar distributions of species richness among the major groups (Fig. 6; see also Table S- 7). This does not reflect their dominance or biomass, and represents simply a species listing; note also that these taxa vary considerably in cell size. No single species or group was found to predominate the samples. Higher numbers of species were seen in the Chrysophytes (*Dinobryon* spp., *Mallomonas* spp., *Chrysosphaerella*, *Chrysostephanosphaera*), green algae (*Botryococcus*, *Planktosphaeria*, desmids) and

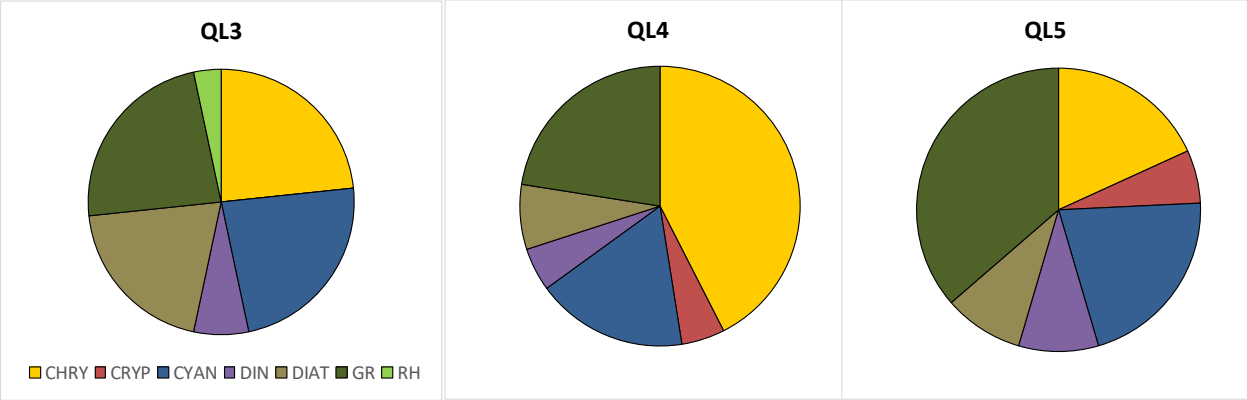

Fig 6. Species numbers in each major taxonomic group in net samples collected at nearshore stations QL3, QL4 and QL5, mid July, Leonard Lake; GR=Chlorophyta (Green algae), CHRY=Chrysophyta , DIAT=diatoms, CRYP=Cryptophyta, DIN = Dinophyta; RH=Rhaphidiophyte

Cyanobacteria (*Planktolyngbya*, *Synechococcus*, *Cyanodictyon*, *Woronichinia elorantae*). It is of note that the cyanobacteria *Dolichospermum* (*D. lemmermanii*, *D. planctonicum*) were present at all three sites, demonstrating a wide distribution (at low population levels) at this time across the inshore areas not observed at the offshore site. In addition, *Gonyostomum semen* was present at station QL3 at low levels of abundance. This species has developed highly problematic slime-producing blooms in acid-impacted lakes with high DOC and low abundances of large grazers (Trigal et al. 2013). It has been recorded in other lakes in this region (e.g. Findlay et al 2005, S. Watson unpublished data), but was not observed in any other samples in Leonard Lake.

August plankton

The algal and cyanobacterial assemblage of the lake was assessed in far greater detail in August from composite, discreet depth and net samples collected at several sites across Leonard Lake for quantitative and qualitative analysis of dominant taxa present at offshore and inshore sites. (Figs 7,8,9, S-4; Table S-7).

The depth-composite sample from the central site (station 36) collected in early August had a total algal biomass of 512 µg/L, which was significantly lower (~75%) than seen at this site in July and

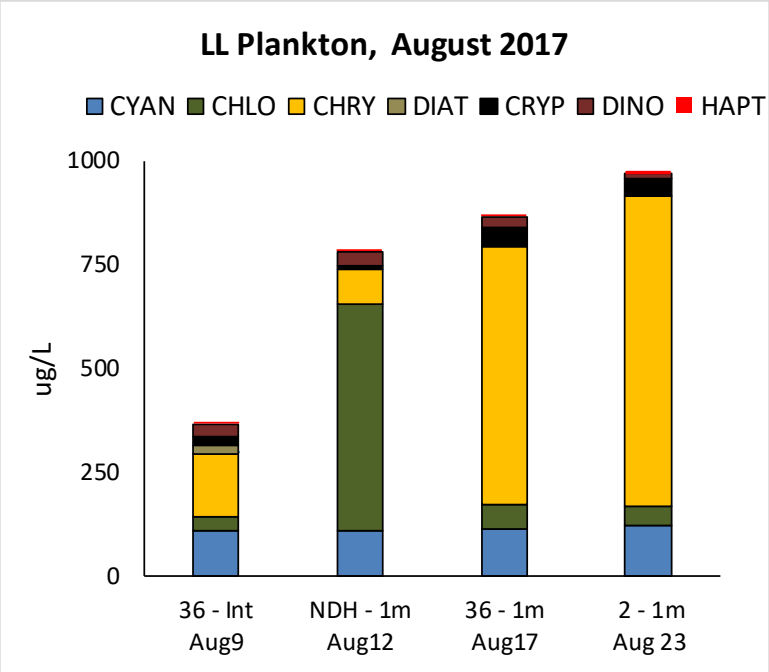

Fig 7. Phytoplankton biomass and composition at stations 2, 36 and NDH in 1m and integrated samples collected during August, Leonard Lake. CYAN=Cyanobacteria, CHLO=Chlorophyta (Green algae), CHRY=Chrysophyta , DIAT=diatoms, CRYP=Cryptophyta, DINO = Dinophyta; HAPT=Haptophyta

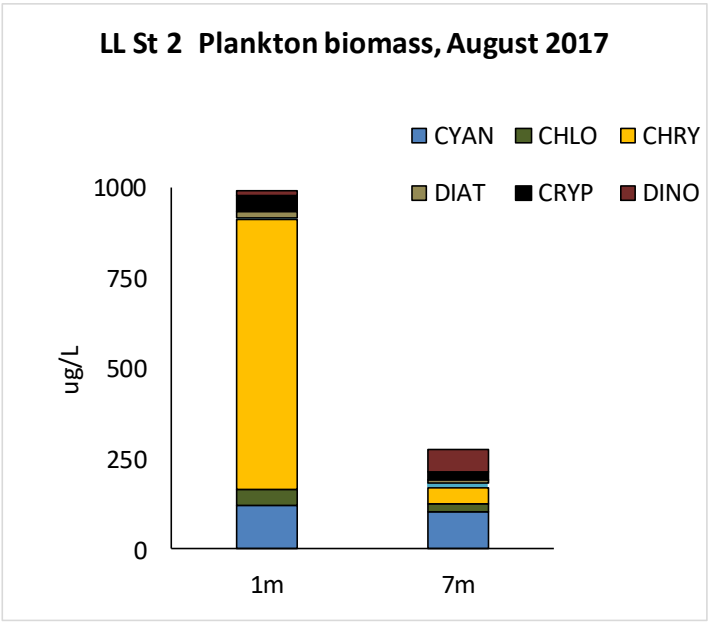

Fig 8. Phytoplankton biomass and composition in 1m and 7m samples, station 2, Leonard Lake August 23, 2017. CYAN=Cyanobacteria, CHLO=Chlorophyta (Green algae), CHRY=Chrysophyta , DIAT=diatoms, CRYP=Cryptophyta, DINO = Dinophyta

more evenly divided among different taxonomic groups (Fig. 7), with a lower abundance of mixotrophic species. Diatoms and chrysophytes were again major constituents (32%, 29% TB respectively), dominated by the chain-forming pennate diatom *Tabellaria fenestrata* (30%TB), *Synura* spp. (15%) and a variety of mixotropic chrysoflagellates (*Uroglena* sp. and small-celled ochromonads; 5%TB). Cyanobacteria showed a modest increase from July (from 24 µg/L to 106 µg/L), again dominated by small filamentous and colonial picocyanobacteria; *Dolichospermum lemmermannii* was present but at very low abundance (14µg/L or 3%TB).

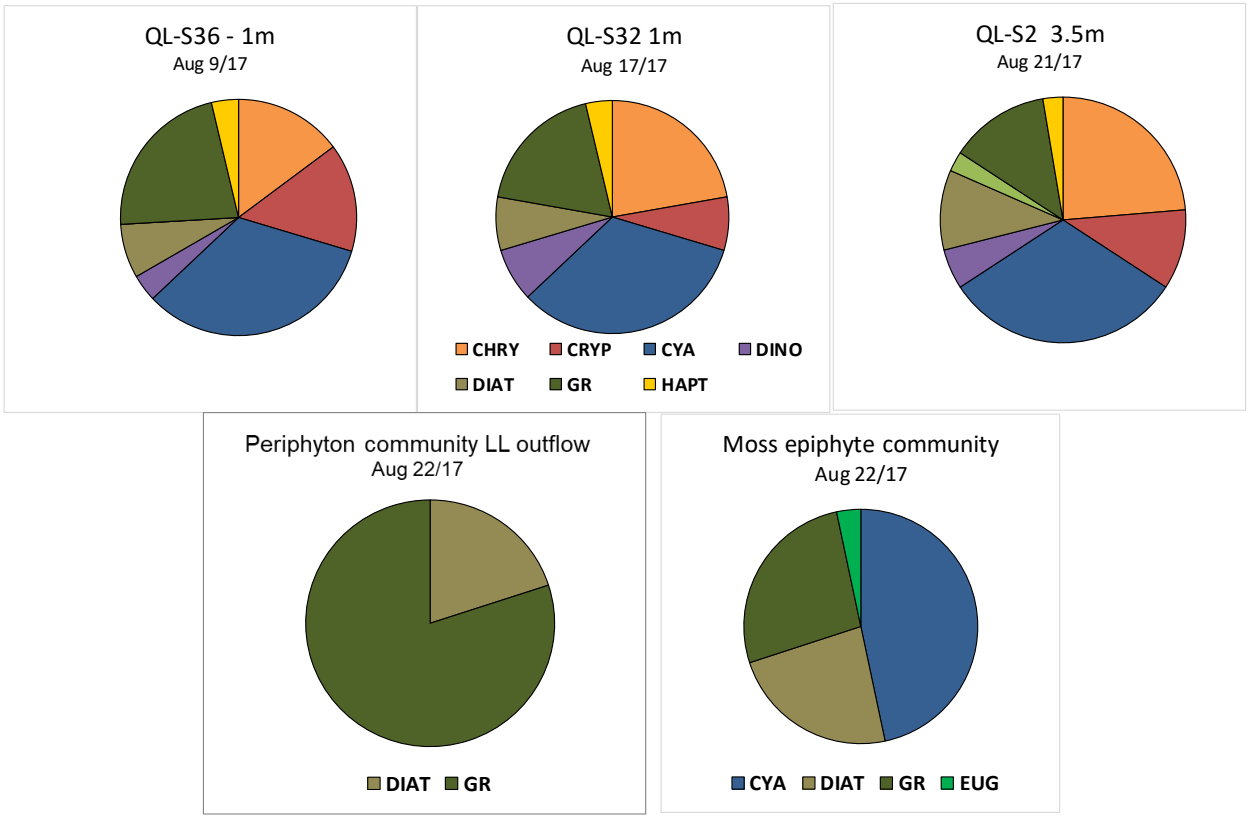

Fig 9. Species numbers in each major taxonomic group, mid August, Leonard Lake. in (Top row) net samples from stations QL S36, QL S32 and QL S2 (3.5m); (Bottom row) periphyton at shoreline site near outflow to lake; on rocks (left) and moss (right); CHLO=Chlorophyta (Green algae), CHRY=Chrysophyta, DIAT=diatoms, CRYP=Cryptophyta, DINO = Dinophyta; HAPT=Haptophyta

There was a marked difference in community composition in the surface (1m) sample collected from the north end of the lake (station NDH) which was something of an anomaly (Fig.7). The total biomass was moderately higher (800µg/L) but dominated by small celled green algae *Koliella* cf *corcontica* which are not commonly seen at high densities in the open water. This species is usually most abundant in terrestrial habitats, and the population may have originated on the shoreline and been introduced to this site by local runoff. Other species present were generally representative of the central site community composition. *Dolichospermum lemmermanni* was

present in low abundance (~3%TB), together with trace levels of the potentially toxic cyanobacterium *Aphanizomenon gracile* (<1%TB).

The 1 m samples from the central and south monitoring stations collected later in August showed much higher biomass than the earlier samples (Fig. 7), mainly due to large populations of colonial scaled chrysophyte flagellates (*Synura cf. splendida, S.* cf. *petersen*ii., *Chrysosphaerella longispina*) which accounted for ~61% of the total biomass both sites (Fig.8.). These and other chrysophytes can produce strong cucumber-fishy-rancid taste and odour (Watson 2010), and may have been the source of fishy odours reported recently (in early spring) near the outlet to the lake (K. Riley, personal communication, 2017). Cyanobacteria were present but not significant, and mainly composed of small picocyanobacteria (*Cyanodictyon planktonica, C. reticulatum, Merismopedia tenuissima, Radiocystis geminata, Aphanocapsa delicatissima, Chroococcus minutus*) and fine filaments of *Planktolyngbya limnetica*. *Dolichospermum lemmermannii* was also present at both sites, but at very low abundance (1-5µg/L).

Comparison of samples collected near the surface (1m) and bottom (7m) at the southern site 2 showed marked differences in community composition (Fig. 8), demonstrating clearly that the water column was not well mixed, but contained a heterogeneous plankton population even at this shallow offshore site. This was consistent with the temperature and DO profiles which showed a strong stratification, a thermocline at ~4m and an anoxic bottom layer (Fig S-5). Compared to the surface, the plankton biomass at 7m was significantly lower (280 µg/L); *Synura* spp. were rare (only ~6µg/L) and the community was composed largely of small-celled cyanobacteria (notably *Romeria*), mixotrophic/ heterotrophic flagellates and degrading algal material. Cyanobacteria biomass was low and remarkably similar in surface and bottom samples and in both cases, dominated by a variety of picocyanobacteria and small, non N_2 fixing filamentous forms

(*Planktolyngbya, Pseudanabaena*). The erratic chl-a florescence profile peaked between 5-6 m depth (Fig S-5), but was not correlated with the dramatic change in biomass between 1m and 7m. Similarly, the PC profile suggested an increase in cyanobacteria with depth, which more likely reflected increases in dissolved organic material which fluoresces at similar wavelengths and can interfere with these readings.

Unlike the variance seen among the quantitative samples, the qualitative analysis of August net material (stations 36, 32) and a depth sample (station S2, at 3.5 m) showed very similar species representation, with no clear dominance by any one species or group (Fig. 9). Large bloom-forming cyanobacteria taxa were rare but a few cells of *D. lemmermanni* were recorded in the net hauls taken at two of the three sites (stations 2 and 36).

August periphyton

In response to a property owner's report of thick littoral[28] growth near the outflow to the lake, two samples were collected and sent to ATEI for analysis (Station 38; plate S-1; Table S-7). One was composed largely of metaphytic[29] filamentous green algae belonging to the order Zygnematales (Charophyta), and of similar composition to those reported in earlier years, dominated by species of *Spirogyra, Mougeotia* and to a lesser extent, *Zygnema* and *Oedogonium*. None of these taxa was exhibiting reproductive stages and hence they could not be identified to species level, but this kind of green algal growth is typical of inshore areas in many small ponds and lakes, and usually flourishes where there is local nutrient enhancement e.g. from groundwater influx or shoreline inputs. A few diatoms were also present, largely dominated by the cosmopolitan chain-forming species *Tabellaria flocculosa*, which is distributed widely across surface waters but most commonly found in low alkalinity, slightly acidic waterbodies.

Tabellaria flocculosa and other benthic diatoms (*Gomphonema cf acuminatum, G. cf truncatum, Enyconema cf gracilis, Navicula cf cryptocephela, Fragilaria cf rumpens, Achnanthidium minutissimum, Eunotia cf bilunaris*) were also present in the moss sample, collected from the same area. The moss epiphytes also included a diversity of benthic cyanobacteria (notably non N_2-fixing filaments *of Leptolyngbya* (dominant), *Borzia or Hormogonia, Tychonema cf rhodonema Pseudanabaena limnetica* and *Heteroleibleinia cf kuetzingii;* N_2 fixers *(Calothrix* sp ;small colonies of *Nostoc cf paludosum),* together with a colonial chroococcales *(Aphanocapsa sp, Aphanothece cf stagnina, Snowella septentrionalis, Gloeocapsa cf sanguinae, Coelosphaerium kuetzingiana*). *Dolichospermum* spp. (filaments of akinetes[30]) were not observed. Green algae were present as filaments (*Mougeotia, Bulbochaete*),and small unicells (*Pediastrum tetras*, desmids *Cosmarium* spp., *Xanthidium antilopeum*). As is typical of benthic and epiphytic communities, mixotrophic taxa were common, including the euglenophyte *Astasia*[31] , thecate amoeba (e.g. *Difflugia globosa*) and rotifers. Aquatic moss is common in oligotrophic lakes and forms mats at depths down to 30 m, providing a substrate for a diverse community of small epiphytic cyanobacteria and algae.

September plankton assemblages and inshore blooms

The depth composite sample at the central site (36) showed only a slight increase from the August biomass recorded at this site (604 µg/L TB; Fig. 5), and some small shifts in species composition. In particular, there was a significant increase in the abundance of small flagellates, notably *Cryptomonas reflexa* (26%TB), which is ubiquitous to many lakes and a high quality, lipid rich food source for zooplankton. It is of note that while cyanobacteria accounted for ~20%TB, they

[28] Epiphyton: growing in the littoral or nearshore zone attached to the bottom or to rocks and other surfaces

[29] Metaphyton: growing attached or free-floating among or in near shore plants, rocks, debris etc. sometime floating in mats; some species e.g. filamentous Conjugales, often have the appearance of 'green cotton candy'

[30] Akinete: vegetative resting cell produced under adverse conditions, often over winters on sediments after the decline of a population

[31] See web video for an entertaining illustration of this taxon https://www.youtube.com/watch?v=UJfc3BTz1tE

were predominantly small-celled filamentous, colonial, and unicellular forms, while large bloom-forming species - notably *Dolichospermum* - were not observed at this site.

In contrast, all bloom samples collected at the inshore sites Q6-Q10 (see plate S-1) contained high numbers of live or decaying *Dolichospermum lemmermannii*. Most of these blooms were located on the south or east shorelines, where they may have formed as a result of wind or surface currents transporting cells inshore; however, as noted above, there was no evidence of the presence of any significant offshore population in the central site sample. Alternatively, they may reflect localised inputs of nutrients. These surface blooms degraded after less than a week, forming milky-like scums of decaying material and clusters of akinetes, resilient, thick-walled resting 'spores' produced by these cyanobacteria at the end of a population cycle and which act as 'seed beds' on sediment surfaces, germinating under favourable conditions. Nevertheless, the presence of these blooms in these shoreline areas, where there is an enhanced risk of human and animal exposure, represents a potential issue in Leonard Lake that needs further investigation. No toxin analyses were carried out on these samples.

October plankton assemblage, central site

The mid-October plankton sample again showed a moderate increase in total biomass from the previous month (700 µg/L), and a shift in species composition towards an assemblage resembling the spring community (Fig. 5). Phytoplankton biomass was dominated by chrysophytes (60%TB), notably the large colonial taxa *Chrysosphaerella longispina* (14%TB), *Dinobryon* spp. (*D. divergens, D. bavaricum*) and *Synura*, while small celled cryptophytes (C. *reflexa*, *Plagioselmis nanoplanktica (*formerly called *Rhodomonas*) were minor constituents. Cyanobacteria accounted for ~30%TB and were again dominated by small celled taxa, notably *Chroococcus minutus* (9%TB), but *D. lemmermannii* and other large bloom-forming taxa were not observed.

Conclusions

Overall, the LLSA data from Leonard Lake 2017 show distinct seasonal and spatial patterns in phytoplankton biomass and community composition, that are poorly correlated with nutrients (TP, etc.), chl-a and other measures. This clearly illustrates the importance of basing any assessments of the trophic status of the lake on multiple parameters. It also demonstrates a need to evaluate site selection, sampling frequency and depth(s) carefully in order to fully capture the range of variance in these measures and optimise the efficiency of future long-term monitoring programmes.

Summary of major results

The collective data from 2017 indicate that Leonard Lake has a low-to-moderate level of productivity and a generally robust and diverse algal community, dominated by lipid-rich diatoms and flagellates (representing high quality food for the upper food web) and small celled picocyanobacteria and green algae. However, the water quality data show nutrient levels that

periodically exceed those measured by the provincial and regional agencies, who have largely concentrated their efforts on spring samples collected as depth composites.

The 2017 data show several important results:

- A significant vulnerability to low DO levels at several sites across the lake (not just the long term, central monitoring site), which develop bottom hypoxia or anoxia. This has implications for both internal nutrient loading and fish/aquatic invertebrate habitat (particularly cold-living species which may migrate to these bottom sites during warm summer months)
- Appreciable seasonal and spatial variance in the phytoplankton abundance and community composition, which at times reaches mesotrophic levels of productivity which may be underestimated by current monitoring programmes.
- Low abundances of bloom-forming taxa *Dolichospermum* spp. across much of the lake, typical of oligotrophic systems where these potentially nuisance algae are present at background levels (but can exploit localised or gradual increases in response to increased nutrient supplies).
- Brief but visibly dense cyanobacteria surface blooms at several inshore sites in late summer, possibly reflecting localised enrichment from the shoreline, or as a result of wind and wave activity concentrating the cells in these inshore areas. Such blooms may contain toxins, an issue that should be further assessed. These toxins can have serious effects if ingested by pets or humans (e.g. during recreational activity). Climate change is likely to increase the frequency of these blooms, as a result of increased open water periods, severe storms with flash runoff, altered lake circulation patterns and increased surface water temperatures, all of which favour nuisance blooms.
- The seasonal and spatially-resolved phytoplankton data represent a vital resource against which future change can be assessed, which if possible, should be continued along with an assessment of water quality and particularly, inshore and internal nutrient loading.

Ongoing stewardship and monitoring - recommendations

- Above all, discrepancies in site locations, redundant sampling efforts and differences between agencies in sampling and analytical protocols (interlab comparisons) need to be rigorously evaluated.
- The resiliency of current wastewater systems and potential impacts on Leonard Lake should be evaluated and acted on
- The extent and level of internal loading should be investigated
- A bloom response protocol should be established in collaboration with provincial and district agencies to ensure a rapid, timely response and rigorous assessment of toxins and other risk factors.

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Supplemental material

Fig. S-1

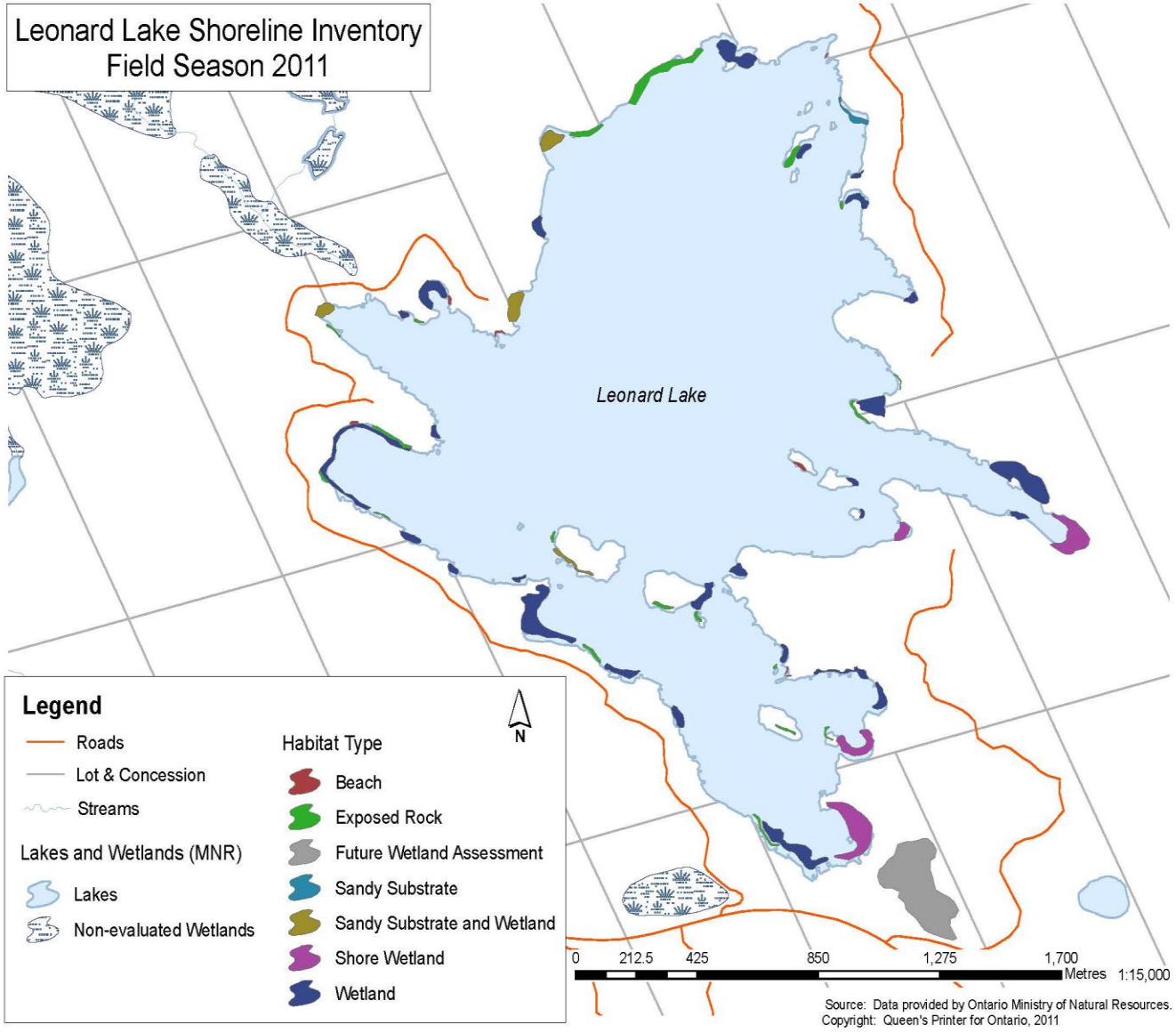
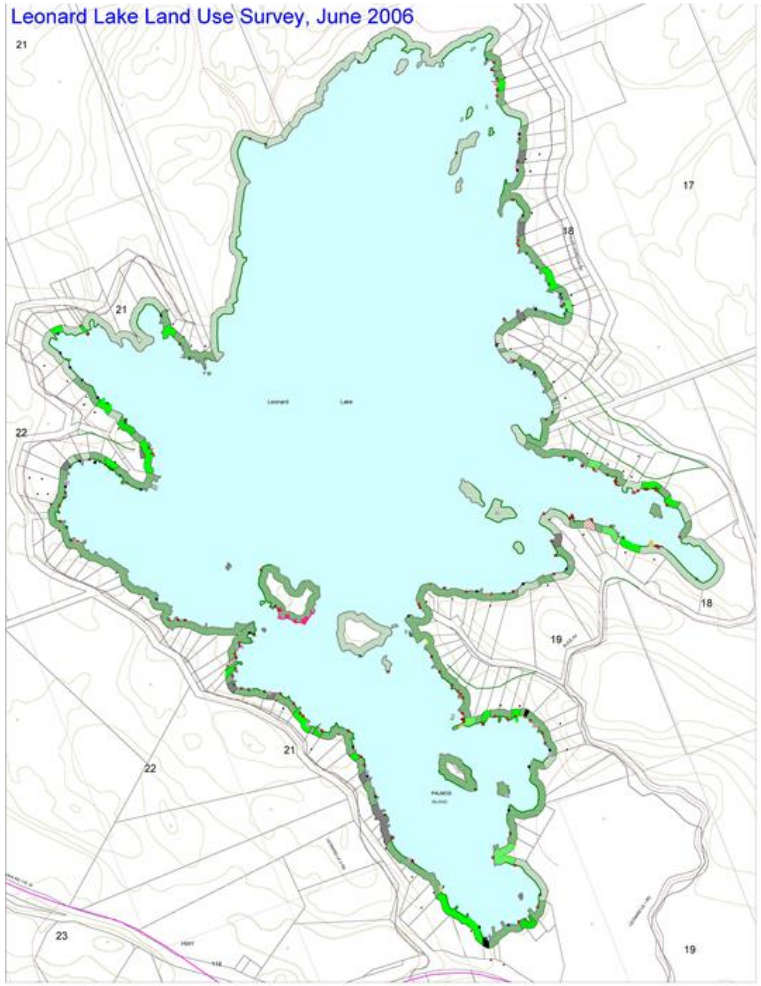

Leonard Lake Shoreline Inventory
Field Season 2011
Leonard Lake
Legend
Roads
Lot & Concession
Streams
Lakes and Wetlands (MNR)
Lakes
Non-evaluated Wetlands
Habitat Type
Beach
Exposed Rock
Future Wetland Assessment
Sandy Substrate
Sandy Substrate and Wetland
Shore Wetland
Wetland
N
0 212.5 425 850 1,275 1,700
Metres 1:15,000
Source: Data provided by Ontario Ministry of Natural Resources.
Copyright: Queen's Printer for Ontario, 2011

Fig. S-2: Leonard Lake Shoreline Use survey 2006 (source: District Municipality of Muskoka)



Legend

shorelineleonardMAP by Shoreline

- NB (6)
- NM (2)
- NR (161)
- NS (145)
- OMMB (2)
- OMR (2)
- OSD (34)
- RC (4)
- RS (4)
- RW (4)
- SWS (36)
- SWW (18)
- YLU (10)

Shoreline Length and Percentages

Shoreline	Type	Length_m	Percent
NB	Natural Beach	127.06	0.36
NM	Natural Mud	49.49	0.14
NR	Natural Rock	18,866.87	54.07
NS	Natural Shrub	12,709.43	36.43
OMMB	Man Made Beach	38.41	0.11
OMR	Marine Railway	325.56	0.93
OSD	Deck	349.01	1.00
RC	Cement Ramp	81.00	0.23
RS	Stone Ramp	72.85	0.21
RW	Wood Ramp	35.04	0.10
SWS	Stone Shore Wall	1,262.32	3.62
SWW	Wooden Shore Wall	390.51	1.12
YLU	Unbuffered Lawn	583.28	1.67
	Total	34,890.85	100.00
	Natural	31,752.85	91.01
	Altered	3,138.00	8.99

Legend

backlotleonardMAP by Backlot

- NFM (25)
- NFT (51)
- NO (13)
- NR (12)
- NS (5)
- OR (2)
- OSCO (2)
- YL (5)
- YLB (3)
- YLU (17)

Backlot Area and Percentages

Backlot	Type	Area_m2	Percent
NFM	Mixed Forest	463.12	3.23
NFT	Thinned Forest	4,528.54	31.61
NO	Overgrowth	515.95	3.60
NR	Rocks	2,666.15	18.61
NS	Shrubs	110.92	0.77
OR	Road	403.27	2.82
OSCO	Cottage	211.17	1.47
YL	Landscaping	820.97	5.73
YLB	Buffered Lawn	542.69	3.79
YLU	Un-buffered Lawn	4,061.48	28.35
	Total	14,324.46	100.00
	Natural	3,240.19	22.62
	Altered	11,084.27	77.38

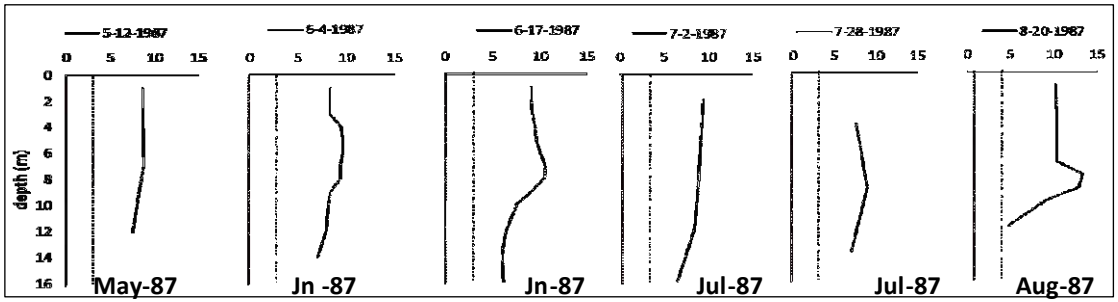
Legend

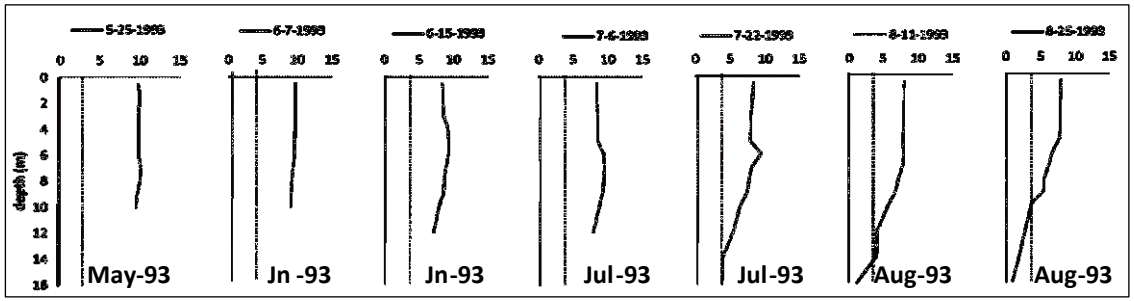
structuresleonardMAP by Structure

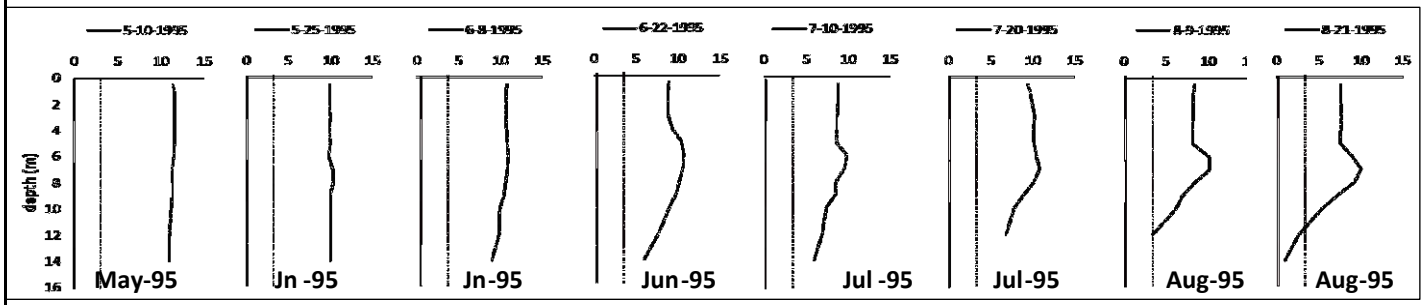
- BHC (2)
- BHC1 (4)
- BHC2 (1)
- BHL (12)
- DC (91)
- DC1 (7)
- DC2 (1)
- DFL (31)
- DP (43)
- OSSC (2)

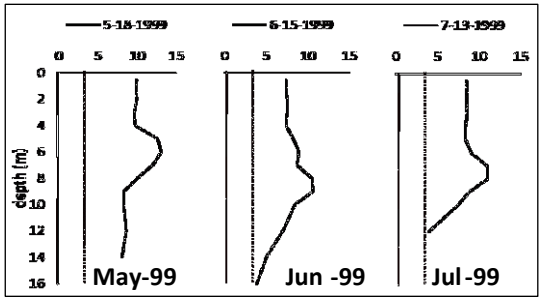
Structure Count

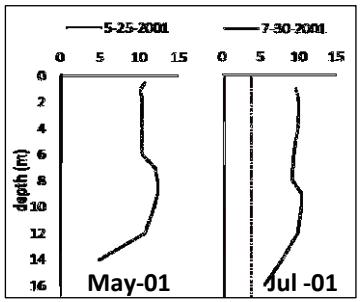
Structure	Type	Count
BHC	Crib Boathouse	2
BHC1	1 Slip Crib Boathouse	4
BHC2	2 Slip Crib Boathouse	1
BHL	Boathouse on Land	12
DC	Crib Dock	91
DC1	1 Slip Crib Dock	7
DC2	2 Slip Crib Dock	1
DFL	Floating Dock	31
DP	Pillar Dock	43
OSSC	Sleep Cabin	2
	Total	194

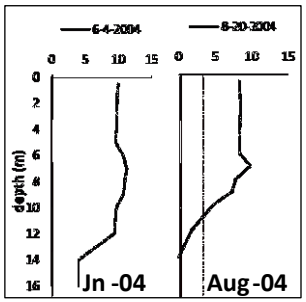


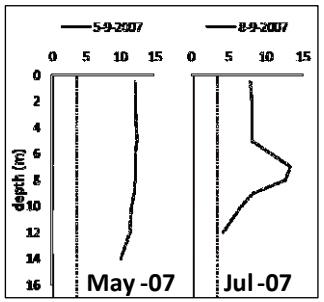


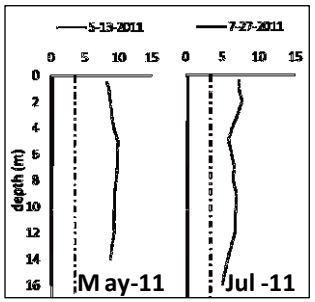


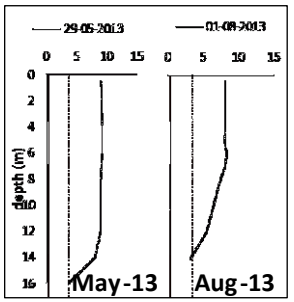












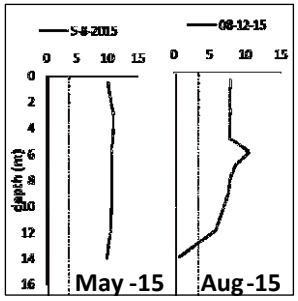


Fig S- 3. Dissolved O_2 profiles at site 36 (central long-term monitoring site, depth 16m) in Leonard Lake, 1987 - 2015. Drawn from historical MOEE data; note reduced sample frequency after 1995. Vertical dotted line at 4mg/L where conditions are adverse for fish.

Fig. S-4. Leonard Lake sampling sites, LLSA 2017

Fig S-5: Leonard Lake August profiles, Sites 2, 32, 36 and NDH

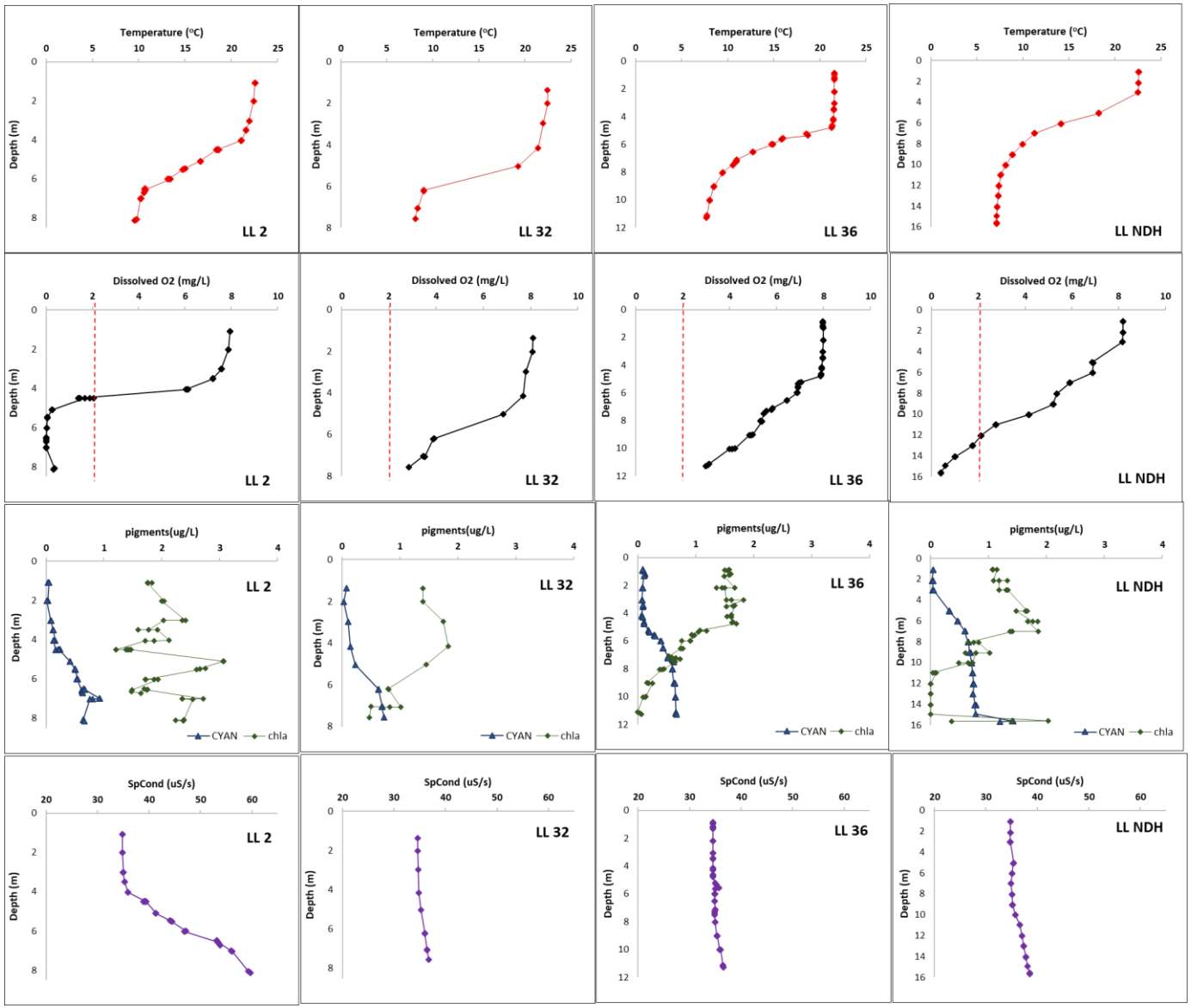


Table S-1: Summary of Leonard Lake major morphometric and average water quality parameters

Parameter	Range or average (1980-2015)	Reference
Location (lat, long)	45.0751 N, -79.4496 W	MNR 2017
Elevation (m asl)	275	MNR 2017
Surface Area (SA) (km^2)	1.95	Ingram & Paterson 2015
Catchment area (km^2)	4.19	Ingram & Paterson 2015
Shoreline (km)	13.9	MNR 2017
Island shoreline (km)	3.7	MNR 2017
Shoreline Development Index	1.4	Calculated, this report
Volume (m^3)	1.33×10^7	MNR 2017
Max depth (m)	18	MNR 2017
Mean depth (m)	6.8	Ingram & Paterson 2015
Residence time (yr)	5.4	Nurnberg 2017
pH	5.5 – 6.7	Ingram & Paterson 2015
Secchi depth (m)	4.1	MNR 2017
Dissolved Organic Carbon (mg/L)	2 – 4.5	Ingram & Paterson 2015
Dissolved O_2 (mg/L), epilimnion	7.5 – 8.8	Ingram & Paterson 2015
Alkalinity (mg/L $CaCO_3$)****	2.8	MOEE, raw data
Conductivity (µS/S)	33-35**	OWRC 1971
Calcium (mg/L)	1-2.5	Ingram & Paterson 2015
Sodium (mg/L)	0.75-3.5	Ingram & Paterson 2015

Chloride (mg/L)	0.5 – 5.4	Ingram & Paterson 2015
Total P (µg/L)	6 – 8*	Ingram & Paterson 2015
Total N (µg/L)	160-280*	Ingram & Paterson 2015
NO_3 (N, µg/L) ****	45.3	MOEE, raw data
NH4 (N, µg/L) ****	24.6	MOEE, raw data
TKN (µg/L)****	245.2	MOEE, raw data
Chlorophyll-a (µg/L) ****	2.4****	MOEE, raw data
Algal biomass (µg/L)	350 - 1966	This study
E. coli (cfu/100 mL)***	1-30	MLA 2016
Total coliform (cfu/100 mL)***	27-129	MLA 2016

*spring data
**1971 data
*** Inshore sites; see report
**** 2001-2015 yearly average

Table S-2: summary of long-term data from Leonard Lake spring samples collected at the central monitoring site, DMM

Lake	Site ID	Site Description	(DMS)	(DMS)	Date	(µg/L)	(µg/L)	%RSD	Collector
LEONARD	1	Stn 1, N end	450453	792641	19-May-02	7.1	11.4	33.3	LPP Volunteer
LEONARD	1	Stn 1, N end	450453	792641	19-May-03	7.8	6.8	9.9	LPP Volunteer
LEONARD	1	Stn 1, N end	450453	792641	02-Jul-04	5.4	5.5	1.4	LPP Volunteer
LEONARD	1	Stn 1, N end	450453	792641	08-May-05	6.3	5.6	8.5	LPP Volunteer
LEONARD	1	Stn 1, N end	450453	792641	03-Jul-06	7.3	6.5	8.4	LPP Volunteer
LEONARD	3	Mid Lake, deep spot	450430	792646	07-Jun-04	7.1			District Municipality of Muskoka
LEONARD	4	Mid Lake, Deep Spot	450428	792637	12-May-09	4.7	4.3	6.3	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	02-May-10	4.8	8.2	37.0	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	08-May-11	6.6	6.2	4.4	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	20-May-12	4.8	5.0	2.9	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	19-May-13	6.2	4.0	30.5	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	18-May-14	7.6	12.6	35.0	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	11-May-15	5.4	5.6	2.6	LPP Volunteer
LEONARD	4	Mid Lake, Deep Spot	450428	792637	22-May-16	4.2	3.6	10.9	LPP Volunteer
overall average							**6.3**		
	stdev						**2.1**		
	%RSD						**14.7**		

Table S-3: Major taxa reported in MOECC survey of Leonard Lake zooplankton (1984)

Calanoid copepodid
Calanoid nauplius
Chaoborus flavicans
Chaoborus punctipennis
Cyclops scutifer
Daphnia ambigua
Daphnia catawba
Daphnia longiremis
Diacyclops bicuspidatus thomasi
Diaphanosoma birgei
Diaphanosoma brachyurum
Epischura lacustris
Epischura lacustris copepodid
Eubosmina longispina
Holopedium glacialis
Leptodiaptomus minutus
Leptodiaptomus sicilis
Mesocyclops edax
Tropocyclops prasinus mexicanus

Table **S-4**: Aquatic Invertebrate Surveys, Leonard Lake Site 1**

	2005	2006	2010	2014	2011	2014	Leonard L. avg.	Muskoka avg**
Richness	14	16	14	14	14	19	15.17	14
% EOT	22	17	20	24	25	29	22.83	22
% Chironimids	12	11	9	19	16	15	13.67	12
% Predators	23	27	21	22	29	30	25.33	23
% Shredders	3	3	3	6	4	8	4.5	3
% Collectors/ Gatherers	70	60	69	69	66	58	65.33	70
Hilsenhoff Index***	6.10	5.68	5.98	5.96	6.09	5.87	5.95	6.1

*Reference site

**147 samples from 76 reference sites (2004 – 2011) from 9 mesotrophic, 26 oligotrophic lakes

***indicative of organic pollution; low scores indicate good water quality

Table **S-5** Leonard Lake qualitative sampling 2017: site location, collection information and reporting

Station	Date	Location	GPS Coordinates	Collection Observations & Notes	Secchi (m)	Temperature (oC)								CSI Volunteer
						0m	8 m	7 m	6m	5m	4m	3m	2m	1m	
QL 1a	28-May-17	Mid Lake (approx)	N45 04.741, W079 27.210 Waypoint 312	Surface, elbow depth, arm sweep; Near 1971 map Central station 36	4.5	18	no temperature taken ===>								G.Roberts, B. Isbister
QT	28-May-17	Mid Lake (approx.)	N45 04.741, W079 27.210 Waypoint 312	Integrated live and lugols net haul (borrowed net) down to 7.0m. Surface elbow sweep.	4.5	18	no temperature taken ===>								G. Roberts, B. Isbister
QL 1b	28-Jun-17	Mid Lake (approx)	N45 04.559, W079 26.778 Waypoint Algae Deep	Surface, elbow depth sweep	4.5	24	no temperature taken ===>								G. Roberts, K. Riley
QT	28-Jun-17	Mid Lake (approx.)	N45 04.559, W079 26.778 Waypoint Algae Deep	Integrated live and lugols; Pump/hose pull down to 7.0m (2x secchi)	4.5	24	no temperature taken ===>								G.Roberts, K.Riley
QL 2	9-Jul-17	Beaver Bay	N45 04.740, W079 27.210 Waypoint 313	Lime green, slimy, cotton candy scum; reported by M. Scarrow. Found in Beaver Bay; E of property 1294 and W of 1304 LL Road 2; Pail used to skim water; Near 1971 map Nearshore Beaver Bay. E of Stn. 32	n/a	22	no temperature taken ===>								G.Roberts, M. Scarrow
QT	18-Jul-17	Mid Lake (approx.)	N45 04.548, W079 26.822 Waypoint	Vertical Sampler; integrated whole water	3.5	20	-	8	12	14	18	18	19	20	G.Roberts, B.Isbister
QL 1c	18-Jul-17	Mid Lake (approx)	N45 04.548, W079 26.822 Waypoint		n/a	20	no temperature taken ===>								G.Roberts, B. Isbister

QL	3	25-Jul-17	Outlet Bay Off Shore	N45 04.679, W079 27.337 Waypoint 315	Outlet Bay out from Scarrow's (1250 LL Road 2) and Riley's dock (1166 1250 LL Road 2); net haul x4 & integrated sample; K.Riley reported. Secchi 4.2m. Near 1971 map Nearshore Outlet Bay Stn. 32	4.2	18	no temperature taken ===>								G. Roberts, K. Riley
QL	4	25-Jul-17	1126 LL Road 2	N45 04.260, W079 27.075 Waypoint 316	Between Greenham's docks 1126 LL Road 2; Net haul x4 & integrated sample; Mark G reported. Too shallow for secchi Near 1971 map Nearshore.Mid way Stn. 31and 40	n/a	18	no temperature taken ===>								G. Roberts, K.Riley
QL	5	25-Jul-17	1163.8 LL Road 1	N45 04.105, W079 26.467 Waypoint 317	Beside McNeely's dock 1163.8 LL Road 1. Net haul x4 & integrated sample. Reported Floating algal mass Too shallow for secchi. Near 1971 map Nearshore N of Stn. 42	n/a	18	no temperature taken ===>								G.Roberts, K. Riley
QL	1d	9-Aug-17	Mid Lake (approx)	N45 04.510, W079 27.906 Waypoint	Surface, elbow depth, arm sweep.	n/a	24	no temperature taken ===>								G.Roberts, K. Riley, M.Green-ham
QT		9-Aug-17	Mid Lake (approx.)	N45 04.510, W079 27.906 Waypoint	Vertical Sampler, Sunny, partially cloudy. No waves; calm. water depth 14.2 m.	3.5	24	-	17	17	21	22	22.5	23	24	G.Roberts, K.Riley, M. Green-ham
QL	n/a	22-Aug-17	1186 LL Road 1	N45 04.318, W079 26.597 Waypoint 363	John Riffel reported **Periphyton.** Sample scraped from rocks; Near 1971 map Nearshore SW Stn. 38	n/a	no temperature taken ===>									G. Roberts M. Greenham

QL 6	14-Sep-17	1208 LL Road 2	N45 04.458, W079 27.386 Waypoint 348	Significant bloom b/w Wilde's and Caravaggio's; sample collected at Caravaggio's who reported green shore scum. Whitish collected vertical sampler 3pm; reported Sept 14th to MOE Spill Action Centre ref no. 8716-AR7PTB; Near 1971 map SW Stn. 31. East Bay	n/a		n/a ===>							G. Roberts
QL 7	19-Sep-17	LL Boat Launch	N45 03.769, W079 26.495 Waypoint 349	2010 Highway Woods; Reported by Hans Heeneman; Skimmed sample off lake surface; along shoreline, not water column; reported Sept 19th to MOE Spill Action Centre ref no. 4531-ARCQ3M; Oily scum near boat launch collected. 1971 map Nearshore Stn. 43 Boat Launch South Bay	n/a	21	n/a ===>							G. Roberts, K. Riley, M. Greenham
QT	19-Sep-17	Mid Lake (approx.)	N45 04.543, W079 27.909 Waypoint	Vertical Sampler	3.5m	21	-	18 C	18 C	18. 5C	19. 5C	20C	21 C	22C	G. Roberts, M. Greenham
QL 8	25-Sep-17	1250 LL Road 2	N45 04.672, W079 27.377 Waypoint 357	1250 LL Road 2 Scarrow; sample skimmed near dock 2 feet of water; water very calm, sunny; shoreline stream, approx. 3' -4', of whitish substance approx. 3”x48”; Skimmed water sample off surface. M Scarrow/ K. reported Green ribbons in floating needles. Near 1971 map Nearshore SW Stn. 32 Outlet Bay	n/a	24	n/a ===>							K. Riley

QL 9	26-Sep-17	1250 LL Road 2	N45 04.681, W079 27.388 Waypoint 354	Scarrow 1250 LL Rd 2 over to neighbours; sample skimmed from water surface; Whitish thin mat /ribbons; very calm and sunny, Near 1971 map Nearshore, W of Stn. 32	n/a	22	n/a ===>	K. Riley
QL 10	26-Sep-17	1217 Butter & Egg	N45 05.002, W079 26.975 Waypoint 356	Bright's collected in bay just to the west of cottage, near shore; sample skimmed from water surface; 4m alongshore. Whitish ribbons; very calm and sunny; Near 1971 map Near shore W of Stn. 34	n/a	n/a	n/a ===>	K. Riley
QT	22-Oct-17	Mid Lake (approx.)	N45 04.546, W079 26.906 Waypoint	Sunny, partial cloud, light chop, wind light; It appears lake turned over	3.5	14	14^{o}C ===> lake has turned over	

Table S-6: Method description and MDL, DESC, Trent University Water Quality Centre (metals) and the Biogeochemical Analytical Service Laboratory (BASL), University of Alberta, Edmonton AB (all other listed analyses)

Method ID	Abbrev.	MDL	Method Name	Reference	Method	Instrument
TM-IOG-003	NH_4	0.2 µg/L	Determination of Ammonia in Surface and Wastewaters by Flow Injection Analysis	Standard methods for the examination of water and wastewater (Modified)	Standard methods for the examination of water and wastewater, 22nd Ed, 4500-NH_3-B,H, AWWA 2004.	Lachat QuickChem QC8500 FIA Automated Ion Analyzer
TM-IOG-004	NO_2+NO_3	2 µg/L	Determination of Nitrate/Nitrite in Surface and Wastewaters by Flow Injection Analysis	US EPA 353.2 (Modified)	Determination of Nitrate Nitrite Nitrogen by Automated Colorimetry	Lachat QuickChem QC8500 FIA Automated Ion Analyzer
TM-IOG-005	TDN	7 µg/L	Automated Determination of Total Nitrogen and Total Dissolved Nitrogen by Flow Injection Analysis	Standard methods for the examination of water and wastewater (Modified)	Standard methods for the examination of water and wastewater, 22nd Ed, 4500-N-B, AWWA 2004.	Lachat QuickChem QC8500 FIA Automated Ion Analyzer
TM-IOG-007	TP; TDP	1.4; 1.8 µg/L	Determination of Total Phosphorus and Total Dissolved Phosphorus in Waters by Flow Injection Analysis	Standard methods for the examination of water and wastewater (Modified)	Standard methods for the examination of water and wastewater, 22nd Ed, 4500-P-B, G, AWWA 2004.	Lachat QuickChem QC8500 FIA Automated Ion Analyzer
TM-IOG-013	Chl-a-F	0.2 µg/L	Determination of Chlorophyll a in Water by Fluorometry	Welschmeyer, N.A. 1994. Limnol. Oceanogr., 39(8), 1994, 1985-1992. (Modified)		Shimadzu RF-1501 Spectro -fluorophotometer
	Total Dissolved Metals	See Table 1B	Trace Metals Analysis by ICP-MS https://www.trentu.ca/wqc/	Standard methods for the examination of water and wastewater, 22nd Ed, 3125, AWWA 2004.	Sample run 3 times, 25 instrument reads per run (0.1 s dwell time). Values calculated as mean ± RSD of 75 reads	Inductively coupled plasma mass spectrometry (ICP-MS)

Table S-7: Listing of plankton and benthic algal, cyanobacteria and microzooplankton taxa recorded in samples collected from Leonard Lake, May-October 2017. Sites 36, NDH, 2, 32 – offshore monitoring sites; QL3-QL10 – inshore net sample sites; Peri – periphyton collected near outflow; Moss – epiphyte community associated with aquatic moss sample collected near outflow. Numbers in columns represent month number(s) when species recorded at that site

	Site, month(s) recorded													
Taxon	**36**	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
Cyanobacteria														
Anathece minutissima	5,3,7,8,10													
Anathece sp.	6,8													
Aphanizomenon cf. gracile		8	8											
Aphanocapsa delicatissima	6,8			8										
Aphanocapsa incerta			8											
Aphanocapsa sp.	5,6,8,9,10	8												8
Aphanothece cf. planctonica	5													
Aphanothece cf. stagnina														8
Aphanothece clathrata	5		8											
Aphanothece sp.	8	8	8											
Calothrix sp.														8
cf. Borzia sp. or Hormogonia														8
Chroococcus cf. aphanocapsoides			8											
Chroococcus cf. minimus	6,7,8	8												
Chroococcus microscopicus	10													
Chroococcus minutus	7,8,9,10		8	8										
Chroococcus sp.	10			8										
Clastidium sp.														8
Coelosphaerium kuetzingiana														8
Cyanodictyon filiformis	7,9			8										
Cyanodictyon planktonica	5,6,7,8	8	8			7	7							
Cyanodictyon reticulatum	6,8,9	8	8											
Dolichospermum (=Anabaena) lemmermannii	5,8	8	8		7	7	7	9	9	9	9	9		
Dolichospermum (=Anabaena) planctonicum	5				7					9				

Taxon	Site, month(s) recorded													
	36	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
Eucapsa starmachii														8
Gloeocapsa cf. sanguinae														8
Heteroleibleinia cf. kuetzingii														8
Lemmermaniella palida	8													
Leptolyngbya sp.														8
Limnothrix					7									
Limnothrix cf. redekei	8													
Merismopedia tenuissima	6,7,8,9	8	8			7								
Nostoc cf. paludosum														8
Planktolyngbya limnetica	8		8	8						8				
Planktolyngbya sp.	6,7,8,9,10	8	8	8	7	7	7			9	9			
Pseudanabaena limnetica	6,9													8
Pseudanabaena mucicola	6													
Pseudanabaena sp.	8,9		8											
Radiocystis geminata	6,7,8,9,10	8	8		7	7	7							
Rhabdoderma sp.	8													
Rhabdogloea smithii	8,9				7	7	7							
Rhabdogloea sp.	10		8											
Romeria cf. leopoliensis			8											
Snowella septentrionalis														8
Spirulina major				8										
Synechococcus lineare							7							
Synechococcus sp.	6,8		8											
Tychonema cf. rhodonema														8
Woronichinia sp.	6													
Woronichinia eloranta	8					7								
Chlorophyta and **Charophyta***														
Ankistrodesmus falcatus/fusiformis	8,10	8	8											

Taxon	Site, month(s) recorded													
	36	NDH	2	32	QL3	QL4	QL5	QL6	QL7	QL8	QL9	QL10	Peri	Moss
Ankistrodesmus fusiformis						7	7							
Aphanochaeta flagellates														8
Binuclearia														8
Botryococcus braunii	6,8,10				7	7	7			9	9	9		
Botryococcus cf. pila	7													
Botryococcus protruberans	9						7							
Bulbochaeta														8
Chlamydomonas sp.			8											8
Closterium kuetzingii									9					
Coenococcus planctonica (=Eutetramorus planktonica)	6	8	8											
Collodictyon triciliatum	10		8											
**Cosmarium cf. laeve*		8												
**Cosmarium abbreviatum*														8
**Cosmarium cf. depressum*	5,8,10													
**Cosmarium sp.*	5,8					7	7							8
**Cosmocladium sp.*					7	7	7							
Crucigeniella quadrata	5													
Crucigeniella tetrapedia	5,8,9													
Desmodesmus cf. braziliensis			8											
Didymocystis sp.	8													
Elakatothrix biplex	9													
Elakatothrix gelatinosa	5													
Elakatothrix genevensis	5,6,8,10		8	8		7	7							
Elakatothrix spirochroma	7,8													
Gloeothece linearis			8											
Keratococcus	5,8,9						7			9				
Koliella cf. corcontica		8												
Koliella longiseta	8,9	8	8											

Taxon	Site, month(s) recorded													
	36	NDH	2	32	QL3	QL4	QL5	QL6	QL7	QL8	QL9	QL10	Peri	Moss
Koliella spiculiforme			8											
Merismopedia punctata			8											
Monomastix sp.			8											
Monoraphidium contortum	8,9,10		8											
Monoraphidium griffithii	6,7													
**Mougeotia sp.*													8	8
Nephrochlamys subsolitaria			7											
Oedogonium													8	
Oocystis cf. submarina	8,10	8	8											
Oocystis lacustris			8											
Oocystis nephrocytium	5				7									
Oocystis sp.	8													
Oocystis submarina	8,9		8											
Oocystis submarina v. variabilis	6,8													
Pediastrum tetras	6													8
Pedinomonas sp.	8		8	8										
Planctosphaeria gelatinosa		8		8										
Planktonema lauterbornii	5													
Planktosphaeria gelatinosa	5													
Quadrigula pfitzeri	8,9		8	8										
Quadrigula sp.	6,8			8		7	7							
Scenedesmus cf. disciformis	6	8	8											
Scenedesmus ecornis		8												
Scenedesmus sp.	8	8												
**Spirogyra sp.*	5,8												8	
**Spondylosium planum*	7													
**Staurastrum bullardii*										9				
**Staurodesmus dejectus*				8										
**Staurodesmus incus*	7				7	7	7			9				

Taxon	Site, month(s) recorded													
	36	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
**Staurodesmus sp.*	8		8											
**Staurodesmus triangulare*							7							
Stichococcus sp.					7									
**Teilingia granulatum*	5,6						7							
Tetraedron caudataum	5,8,9		8											
Tetraedron minimum	8						7							
**Xanthidium antilopeum*	8,10	8	8											8
**Zygnema sp.*	6,8		8										8	
Chrysophyta														
Bicoeca sp.									9					
Bitrichia chodatii											9			
Chroococcus limneticus						7								
Chrysococcus sp.	8													
Chrysolykos planktonicus	5,8		8											
Chrysosphaerella longispina	5,6	8	8			7	7							
Chrysosphaerella multispina/ longispina	6													
Chrysostephanosphaera gobulifera	6,8,10		8	8	7	7								
Dinobryon bavaricum	6,7,8,10		8		7	7	7							
Dinobryon bavaricum v. vanhoffnii						7								
Dinobryon borgei						7	7							
Dinobryon divergens	6,7,8,10		8		7	7	7							
Dinobryon mucronatum						7								
Dinobryon pediforme	8	8				7								
Dinobryon sertularia	5,6,10													
Dinobryon suecicum	7	8		8		8								
Epiphyxis sp.	6													
Kephyrion boreale	5,6,7,8													
Mallomonas acaroides	6													

Taxon	Site, month(s) recorded													
	36	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
Mallomonas akrokomos	7,8					7								
Mallomonas caudata	6													
Mallomonas cf. punctifera			8											
Mallomonas crassisquama	8													
Mallomonas duerrschmidtae	5,7					7	7							
Mallomonas elongata	7													
Mallomonas lychenenis/ allorgei						7								
Mallomonas sp.						7								
Mallomonas tonsurata	5													
Ochromonas sp.	6,8,9													
Pseudokephyrion boreale	5,7				7	7	7							
Pseudokephyrion sp.	7,8,10		8	8										
Pseudopedinella cf. pyriformis, P. erkensis		8												
Pseudopedinella sp.	9													
Rhizochrysis limnetica	8		8	8										
Spiniferomonas sp.	10													
Stichogloea doederlenii	9					7								
Stichogloea olivaceae	5,8,10		8		7	7	7							
*Synura cf. splendida***	7													
*Synura petersenii***	5,7,8,9		8			7	7							
*Synura sp.***	9													
*Synura sp.. (S. petersenii, S. spinosa)***	5,6,8,10		8	8	7									
Uroglena sp.				8										
Cryptophyta														
Cryptomonas cf. playturis	5,7,8		8											
Cryptomonas marssonii			8											
Cryptomonas obovata	5,8	8	8	8										
Cryptomonas reflexa							7							

Taxon	Site, month(s) recorded													
	36	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
Katablepharis ovalis	5,6,7,8,9,10	8		8		7	7							
Rhodomonas lacustris (= Plagioselmis nanoplanktica)	5,7,8,9,10	8	8	8	7	7								
Diatoms (Bacillariophyta)														
Achnanthidium minutissimum														8
Asterionella formosa	5,6,7,8,9,10	8	8		7									
Lindivia bodanica (=Cyclotella bodanica) complex	5,6,7,8			8	7	7-	7							
Enyconema cf. gracilis														8
Eunotia cf. bilunaris														8
Fragilaria cf. rumpens														8
Fragilaria sp.	7													
Gomphonema cf. acuminatum														8
Gomphonema cf. truncatum														8
Navicula cf. radiosa	8													
Navicula cf. cryptocephela														8
Synedra acus v. radians					7									
Synedra nanana (=Fragilaria nanana)	6,8,9													
Synedra sp.	7	8												
Synedra tenera (=S.acus)						7								
Tabellaria fenestrata	5,6,8,9	8	8	8	7	7	7		9	9				
Tabellaria flocculosa	8				7					9	9		8	8
Urosolenia eriense	8,9	8	8		7	7	7							
Dinophyta														
Glenodinium sp.	5,6,8				7									
Gymnodinium mirabile	6,7,8,9		8											
Gymnodinium sp.	8,9		8											
Gymnodinium uberrimuum	6,7,8,9,10	8	8		7	7	7	7						

	Site, month(s) recorded													
Taxon	**36**	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
Parvodinium inconspicuum/ pusillum			8											
Peridinium polonicum	7						7							
Peridinium sp.						7	7							
Peridinium willei			8											
Peridinium wisconsiense	8													
Euglenophyta														
Astasia sp..														8
Euglena acus	5,7,10		8											
Euglena sp.	5,6,7,8,10	8	8	8										
Trachelomonas volvocina		8												
Haptophyta														
Chrysochromulina parva	8,9			8										
Ochrophyta - Rhaphidiophceae														
Gonyostomum semens	7,8		8	8	7		7							
Mixotrophs														
Aulomonas perdyi	6,10													
Cryothecomonas scybalophora	5,7,8,9,10	8	8	8										
Gyromitus cordiformis	7,8,10	8	8	8										
Salpingoeca frequentissma	7													
Salpingoeca sp.				8										
Microzooplankton														
Arcella											9			
Askenasia	10													

	Site, month(s) recorded													
Taxon	**36**	**NDH**	**2**	**32**	**QL3**	**QL4**	**QL5**	**QL6**	**QL7**	**QL8**	**QL9**	**QL10**	**Peri**	**Moss**
Ciliate	8		8											
Difflugia globosa	9	8												8
Haltaria sp.	5,8		8	8	7									
Heliozoan	8													
Holophrya	5,6	8												
Mesodinium sp.	8,10	8	8											
Scuticociliates	5	8												
Strobilidium sp.	5,7,8	8		8										
Strombidium sp.	10					7								
Tintinnids	7,8,10		8											
Urotricha (Scuticociliate)						7			9	9	9	9		
Vorticella					7									
Polyarthra	7													
Trichocerca sp.							7							
Cyclopoid copepod					7		7							

* Charophyes indicated with an asterisk

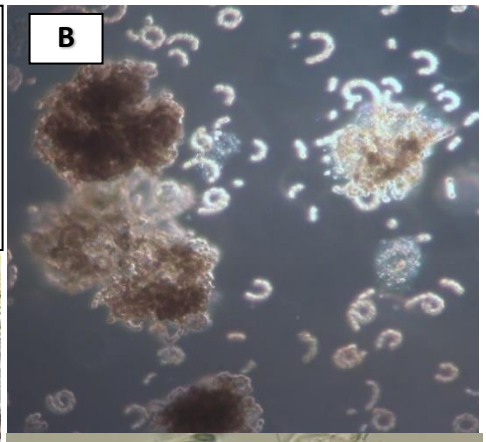
**ID tentative; require SEM for positive identification

Plate S-1: Leonard Lake Periphyton/moss growth reported and sampled August 22, 2017, station 38.

Plate S-2: Leonard Lake images from inshore bloom material, September 2017

A: *Dolichospermum lemmermannii* shoreline bloom at QL6, Sept 14 2017;

B, C: Microscope photo images of *D. lemmermanni* colonies and fragments B: live, x400; C: preserved with Lugols, x200)



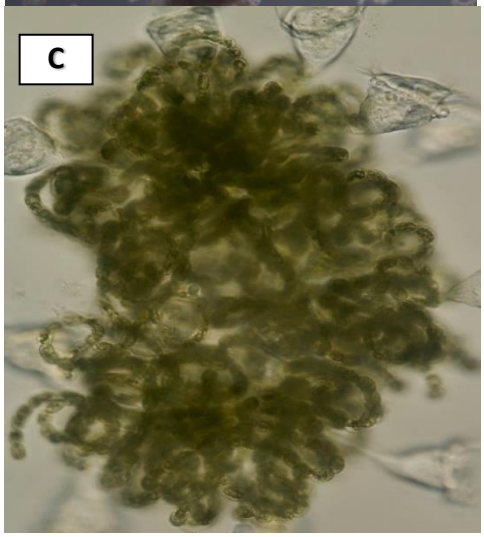


Plate S-3: Leonard Lake images from degrading inshore *Dolichospermum lemmermanii* bloom material, September 2017; top – showing milky, streaky scums; bottom images – microscope photo images of degrading filaments with attached fungal hyphae and debris.