CUMULATIVE EFFECTS ASSESSMENT AND MONITORING
IN THE MUSKOKA WATERSHED

CATHERINE EIMERS, TRENT UNIVERSITY
Research conducted 2012-2015

Canadian
Water
Network

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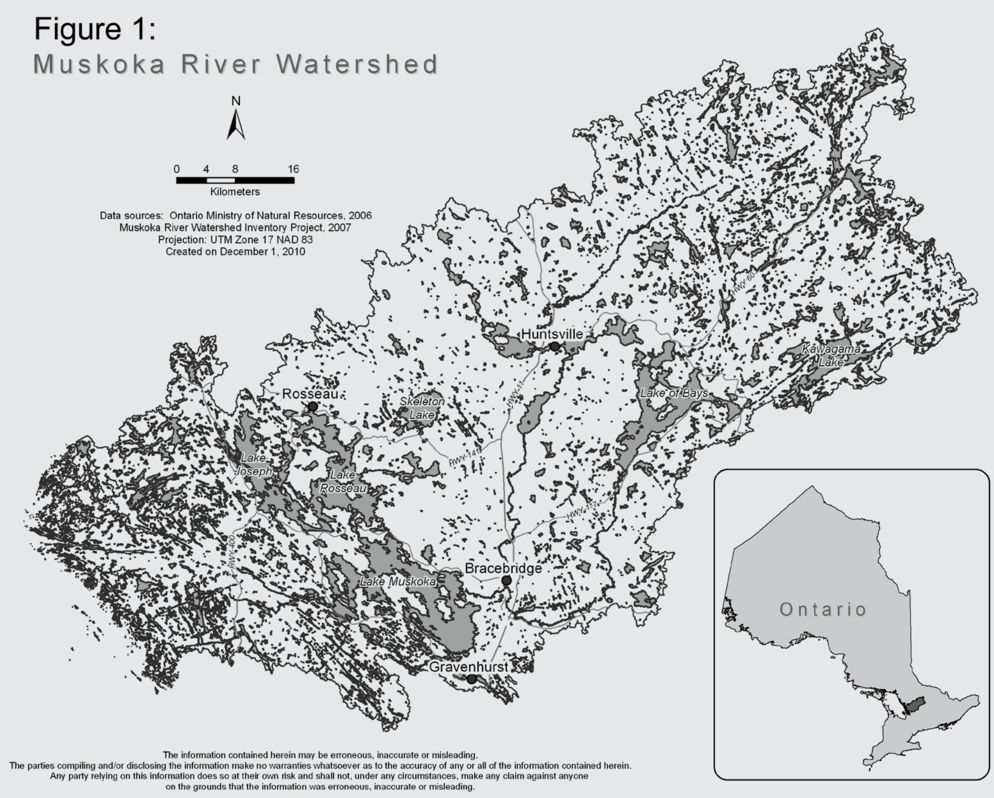

Figure 1: Map of the Muskoka River Watershed.

WHY DID WE DO THIS RESEARCH?

In the heart of Ontario's cottage country, the Muskoka River watershed is home to more than 2000 lakes that are connected by the Muskoka River and its tributaries. Drinking water quality, recreational activities, angling and habitat biodiversity are dependent on the condition of these waterbodies, which are affected by a wide variety of environmental stressors and their interactions. Monitoring is an important component of managing lakes within the Muskoka River Watershed because it provides information about lake conditions over time. This monitoring enables managers to evaluate whether human activities are adversely affecting the physical, chemical and biological quality of a lake.

Historically, the District Municipality of Muskoka's (DMM's) lake monitoring program focused on water clarity and shoreline development. Over three decades of monitoring, shoreline development increased around a number of Muskoka lakes, but phosphorous levels did not increase correspondingly. Other changes were observed over this time period:

- Levels of calcium, an important nutrient for many crustaceans such as zooplankton and crayfish, declined
- Salinity increased as a result of road salt runoff
- Dissolved organic matter increased, which could have implications for nutrient availability, lake thermal properties and biodiversity
- Species composition of phytoplankton changed, causing undesirable changes to drinking water taste and odour

A revision of the original monitoring program in 2005 made lake ecosystem health a monitoring and management priority, but the drivers and implications of many of these changes, as well as the potential for interaction among drivers and cumulative effects were unclear. The monitoring program was in need of further refinement to improve detection and monitoring of cumulative-effects of multiple stressors. Therefore, this project set out to better describe the baseline conditions of waterbodies; establish a common understanding of cumulative effects; make recommendations for updating the current monitoring program; and develop new tools for assessing risk and managing cumulative effects in lakes within the watershed.

WHAT DID WE DO?

A research team consisting of scientists from seven universities and the Ontario Ministry of Environment and Climate Change conducted 11 unique studies, using data collected over three years and historical data from more than three decades of monitoring. The studies:

- Described the chemical, climatic and biological conditions within watersheds, and identified indicators of stressors, biological effects and aquatic ecosystem condition.
- Grouped lakes according to natural habitat type and stressor exposures to determine which groups should be monitored and modelled.
- Examined the mechanisms that underlie the ecosystem responses occurring in the Muskoka River Watershed, to facilitate predictive modeling and selection of indicators relevant to the cumulative effects monitoring program.
- Developed modelling tools that associate stressors and cumulative effects to predict and forecast watershed processes, chemical state and biological condition, and facilitate monitoring of cumulative effects.

WHAT DID WE FIND?

Several key chemical changes occurred over the past few decades in many of the lakes in the Muskoka River Watershed, including decreases in phosphorus and calcium, increases in chloride, and wide variability in dissolved organic matter/carbon concentrations. Our research explored the causes of these long-term changes in chemical condition and the cumulative effects of those changes on lake and stream systems.

PHOSPHORUS

Phosphorus concentrations have declined in many lakes in the Muskoka watershed, and a wide range in phosphorus concentrations have been observed in Harp, Plastic and Dickie lakes (Figure 2). The drivers of long-term phosphorus decline were investigated in Dickie Lake because it has an extremely variable history of past phosphorus concentrations and a comparable range in phosphorus concentrations to that observed across the entire watershed. Additionally, Dickie Lake was an ideal study site since four streams draining into the lake had similarly variable phosphorus concentrations.

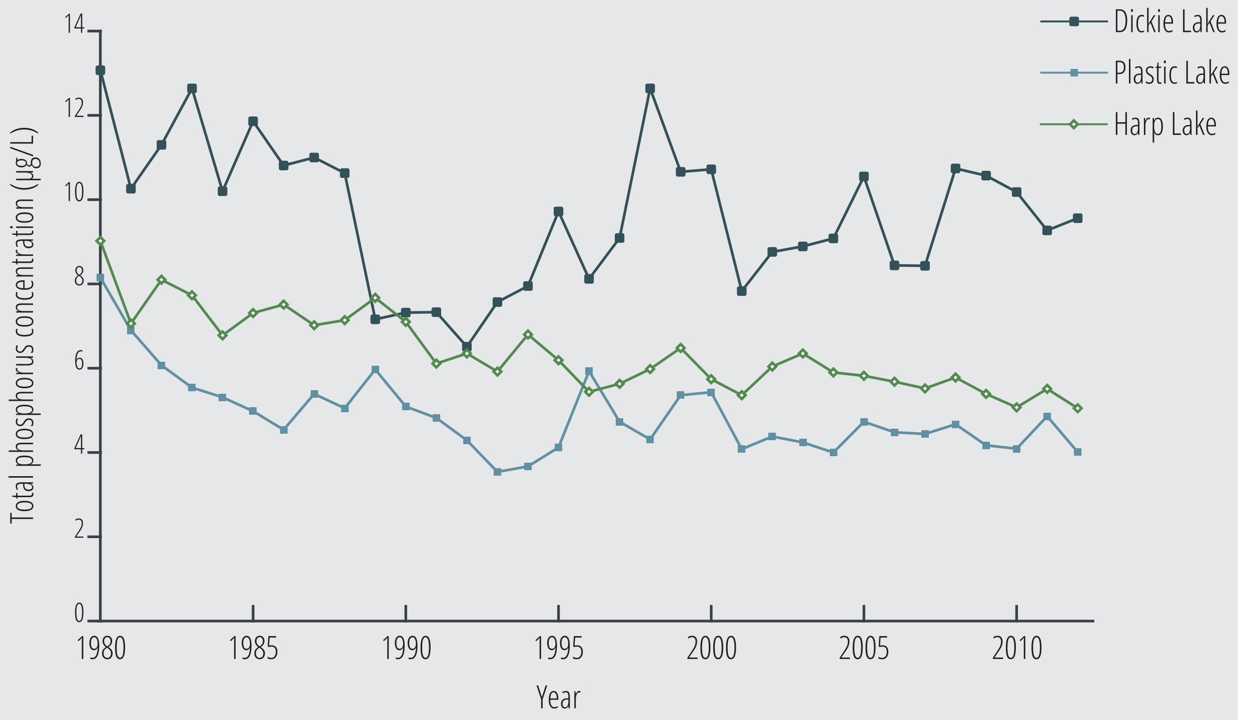

Figure 2: Changes in total phosphorus concentration (ice-free means) over time for Harp, Plastic and Dickie lakes in the Muskoka Region.

Phosphorus concentrations in streams were highest where disturbance had occurred historically, especially within treed wetlands. Road extensions for new developments, undersized culverts and beaver dams can cause flooding of these wetlands. The phosphorus that is released from decaying organic material results in large pulses of phosphorus concentrations in streams and downstream lakes. These large pulses are short-lived, and stream concentrations return to pre-disturbance phosphorous levels within several years following disturbance.

This finding suggests that where possible, disturbance to wetlands and trees in the riparian zone of even small streams should be minimized or avoided. It is most important to avoid disturbing wetlands that are close to lakes and/or along stream channels in order to avoid pulses in nutrient release. Short-term changes to wetland size are currently not considered in the District of Muskoka's Recreational Water Quality Model. Future reviews of this model should consider that changes to the wetland area within catchments may be occurring over time in response to flooding or other land-use disturbances.

CALCIUM

Calcium levels in lakes are also declining across the Muskoka region (Figure 3). Calcium levels are already naturally low, and many lakes are approaching critical levels for aquatic organisms. Small, shallow lakes at higher elevations in small watersheds, with higher runoff and little influence from roads and agriculture are at the highest risk of calcium depletion due to forest harvesting. The decline in levels is related to a reduction in acid rain, which slowed the movement of calcium from soils into lakes.

Logging causes a long-term calcium loss from catchments, because trees aggressively take up calcium and store it. Under currently proposed forest management plans, calcium levels may fall below biologically critical levels in more than half of the 370 lakes studied[1]. In lakes, declines in calcium concentration can lead directly to changes in the biological community, thereby indirectly affecting water availability for municipal and industrial use.

Boxplot distribution of medians and ranges over three decadal time periods based on mean lake values of calcium (Ca) for 104 lakes in the Muskoka River Watershed, $p<.05$.

Lake Ca has declined on average by ~30% from the first decade (1981-1990) to the last decade (2003-2012).

Note: outliers have been indicated as black dots.

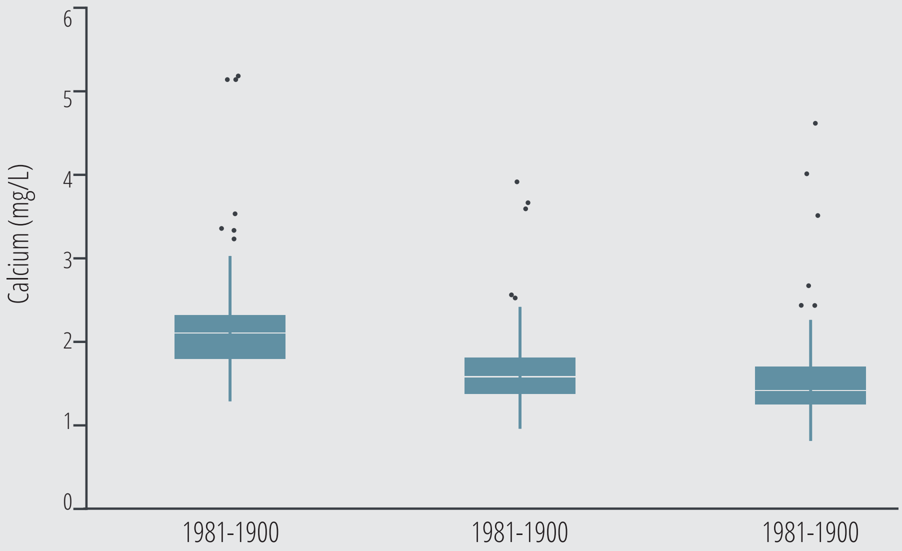

Figure 3: Calcium concentration for 104 lakes in the Muskoka River Watershed for three time periods.

CHLORIDE

De-icing products containing salt are used to keep roads in the region safe in winter. Rising chloride concentrations are common in urban waterways, but levels are also increasing in the relatively rural landscape of the Muskoka River Watershed, even in lakes with a single winter-maintained access road. Many roads are close to lake shorelines, and salts are readily transferred to them by road spray and snowmelt runoff.

A survey of 86 lakes within the watershed showed that salt concentration had a significant influence on the composition of the diatom (algae) community. Diatoms are early indicators of water quality degradation, as they are highly responsive to environmental fluctuations. Experiments with crustacean zooplankton (microscopic animals that feed on algae) showed that salt toxicity was more severe when food was limited, causing slow development, reduced reproduction and low survival (Figure 4).

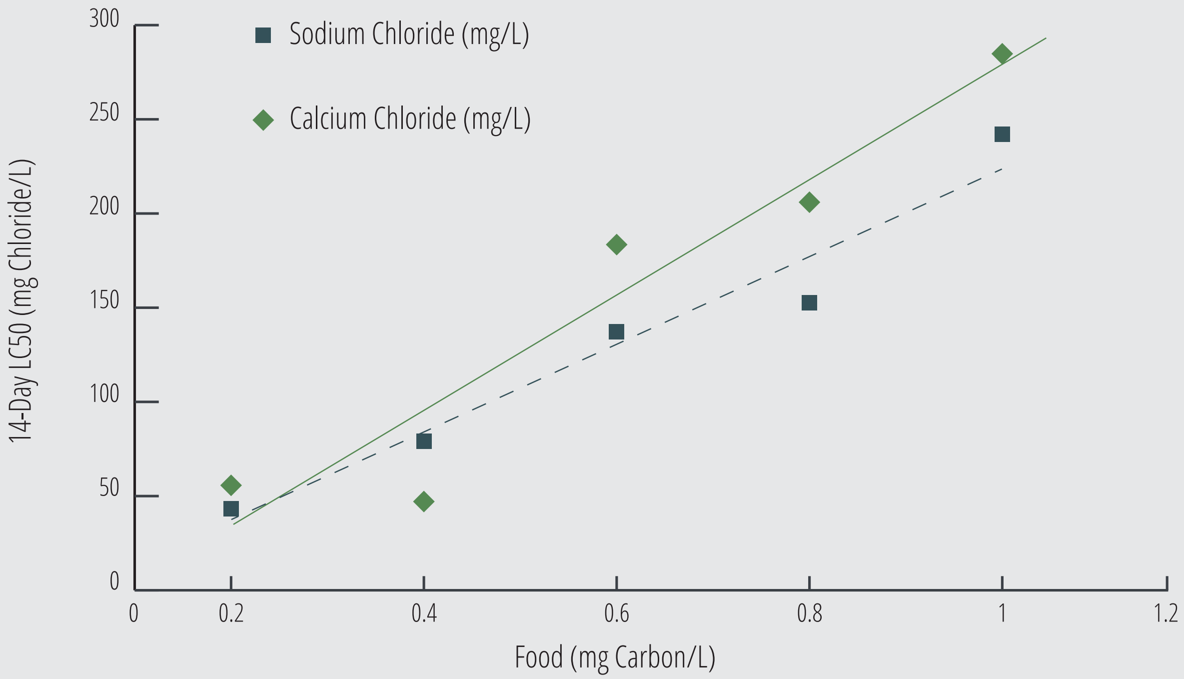

Figure 4: The effect of food quantity on the 50% lethal concentration (14-Day LC50) of sodium chloride and calcium chloride for Daphnia[2]. At lower food levels, the concentration of chloride required to kill 50% of the zooplankton is lower.

Declining phosphorus concentrations cause reductions in food availability (algae) to zooplankton, and could exacerbate the impact of rising chloride concentrations on sensitive lake species. Consequently this cumulative effect may impact biological communities. Up to 90% of the lakes in the Muskoka River Watershed may be sensitive to further increases in chloride, as these lakes are naturally low in nutrients. Any further reductions in phosphorus and calcium could increase chloride toxicity.

DISSOLVED ORGANIC CARBON

Dissolved organic carbon (DOC) concentrations have increased in recent years in a number of lakes in the Muskoka River Watershed, although natural variation is wide (Figure 5). This variability is also associated with differences in nutrient levels, including phosphorus, nitrogen and silica, as well as indicators of acidification, such as pH and alkalinity. In addition to fuelling bacterial growth, DOC concentrations influence interaction among organisms, by altering light penetration and the thermal structure of lakes.

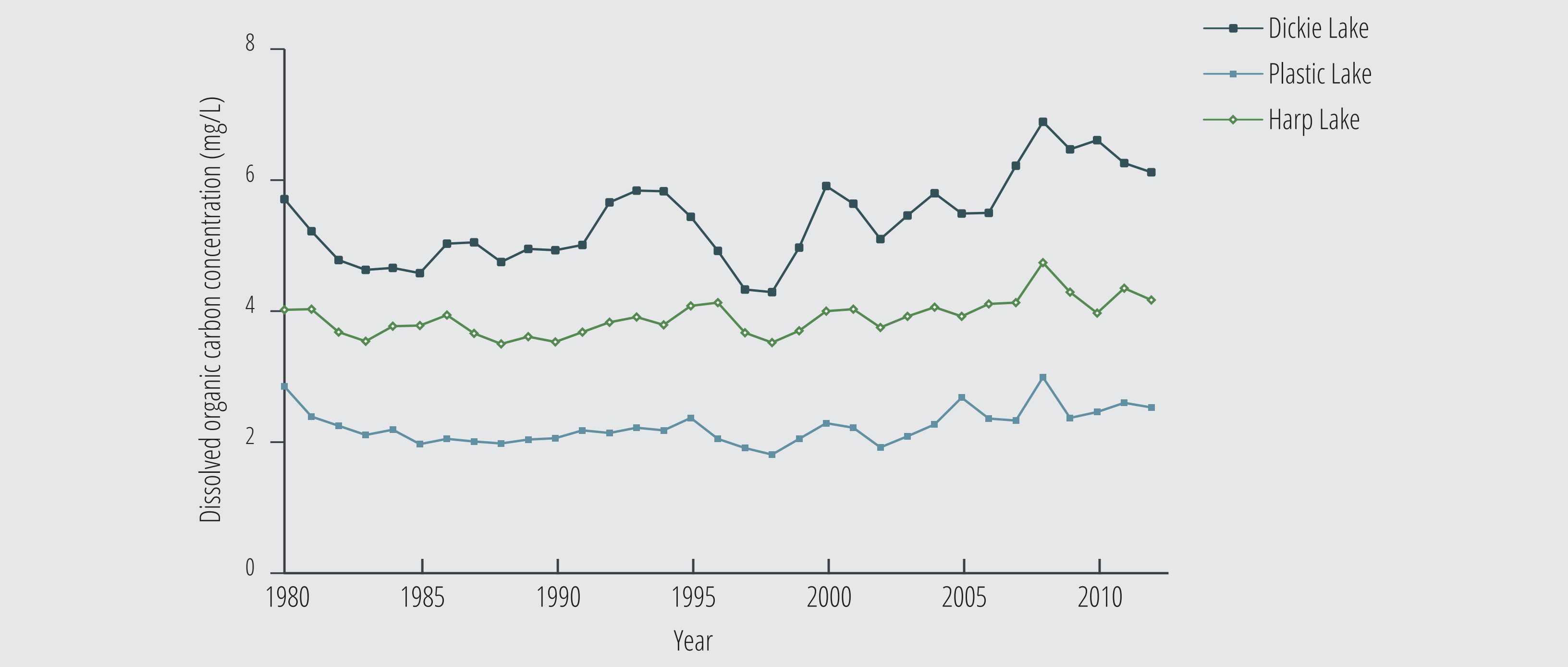

Figure 5: Changes in dissolved organic carbon concentration over time in three monitored lakes (Harp, Plastic and Dickie) in the Muskoka Region.

DOC concentration also plays an important role in many indirect feedback mechanisms that drive biological changes in lakes. For example, lakes with higher DOC and phosphorus concentrations, plus increased thermal stability, provide conditions that favour the growth of cyanobacteria[3]. In contrast, in lakes with higher concentrations of DOC and lower nutrients, the algal community is dominated by chrysophyte algae, which can result in undesirable taste and odour. Higher in the food web, the distribution of several key invertebrates is also associated with differences in DOC concentration amongst lakes.

CLIMATIC AND PHYSICAL CONDITIONS

Records from several weather stations across the region show that daily temperatures in the fall have increased in recent decades (Figure 6). Lakes have warmed, so that complete surface coverage of ice now occurs later in the fall, and ice break-up occurs earlier in the spring. In the summertime, lakes are stratified so that different layers of water temperature exist (i.e., warm surface and cool bottom waters). This stratification now occurs earlier in the spring than it did historically, and the stability of the stratified water column persists later into the fall.

In lakes with higher nutrient concentrations, a more stable water column in summer and fall may increase the potential for development of algal blooms and surface scums (i.e. collection of algae at the surface). The occurrence of these blooms/scums is closely linked to changes in lake properties that are controlled by temperature. Future climate warming may increase the frequency of these nuisance events[4].

Figure 6: Annual temperature and precipitation trends for Beatrice, Muskoka Airport and Dorset weather stations.

BIOLOGICAL CONDITION

Benthic invertebrates (i.e., bottom-dwelling insects, crustaceans, worms, mollusks and related animals) are used as indicators of the biological condition or health of aquatic ecosystems. Surveys of benthic invertebrate communities were undertaken in 112 lakes and 120 streams across the Muskoka River Watershed (Figure 7).

Researchers characterized the normal ranges of benthic invertebrate abundances found in lakes and rivers, and assessed how best to summarize community structure using indices. Certain indices better distinguish reference (i.e., near-pristine) lakes and streams from impacted lakes and streams (i.e. those affected by roads, urbanization, agriculture, dams, garbage dumps, and the non-native spiny water flea).

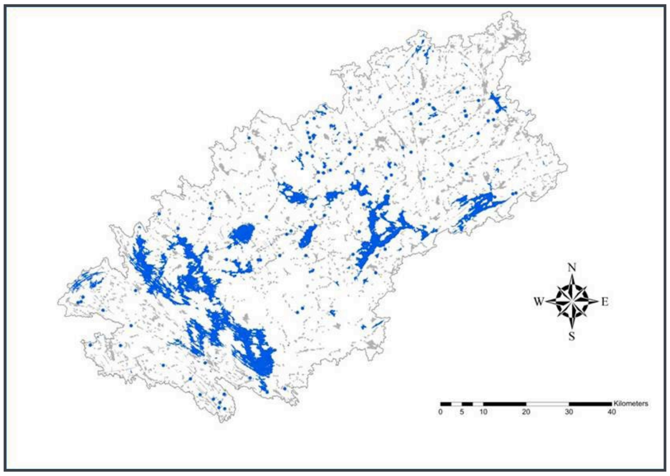

Figure 7: Lakes and streams where benthic invertebrate surveys were conducted.

The animals that strongly distinguished reference lakes from impacted lakes and streams included: insects (particularly Chironomidae (midges), Diptera (true flies) and Corixidae (water boatmen)), Oligochaetes (segmented aquatic worms), Isopoda (sow bugs), Gastropoda (snails) and Hirudinea (leeches). Reference lakes were less diverse compared to impacted lakes, but biodiversity in impacted and reference streams were similar.

To assess the cumulative effects of human activity in the watershed, the team investigated what proportion of the variation in community structure was associated with land-use and human activity, and how large this proportion was relative to the amount of biological variation that is associated with natural factors. Land-use stressors, habitat attributes of the catchment, habitat attributes of the sampled location and water chemistry were studied. For lakes, 63% of the variation among benthic communities was accounted for by these four variables. The dominant factor structuring stream communities was local habitat (19% of variation). Only 2% of the variation in lakes and 1% of the variation in streams was uniquely attributed to land use stressors associated with human activities, although this could explain much more variation when examined in combination with other factors.

Modeling variance in overall community structure suggested that complicated interrelationships exist between habitat, chemical and stressor-exposure factors, which collectively structure benthic communities. The indicators that strongly distinguished the reference lakes from impacted waterbodies should be included in a cumulative-effects monitoring program.

CUMULATIVE EFFECTS

Across the Muskoka landscape, the major stressors influencing waterways include acid rain, climatic variability, shoreline development, land-use change and invasive species. Other potentially relevant stressors not addressed in this project include contaminants from pharmaceuticals and personal care products, and dam construction for energy production. The findings from this project were integrated with previous research completed in the Muskoka River Watershed to develop a better understanding of how stressors are linked to cumulative effects, and how these may directly and indirectly impact freshwater services (Figure 8).

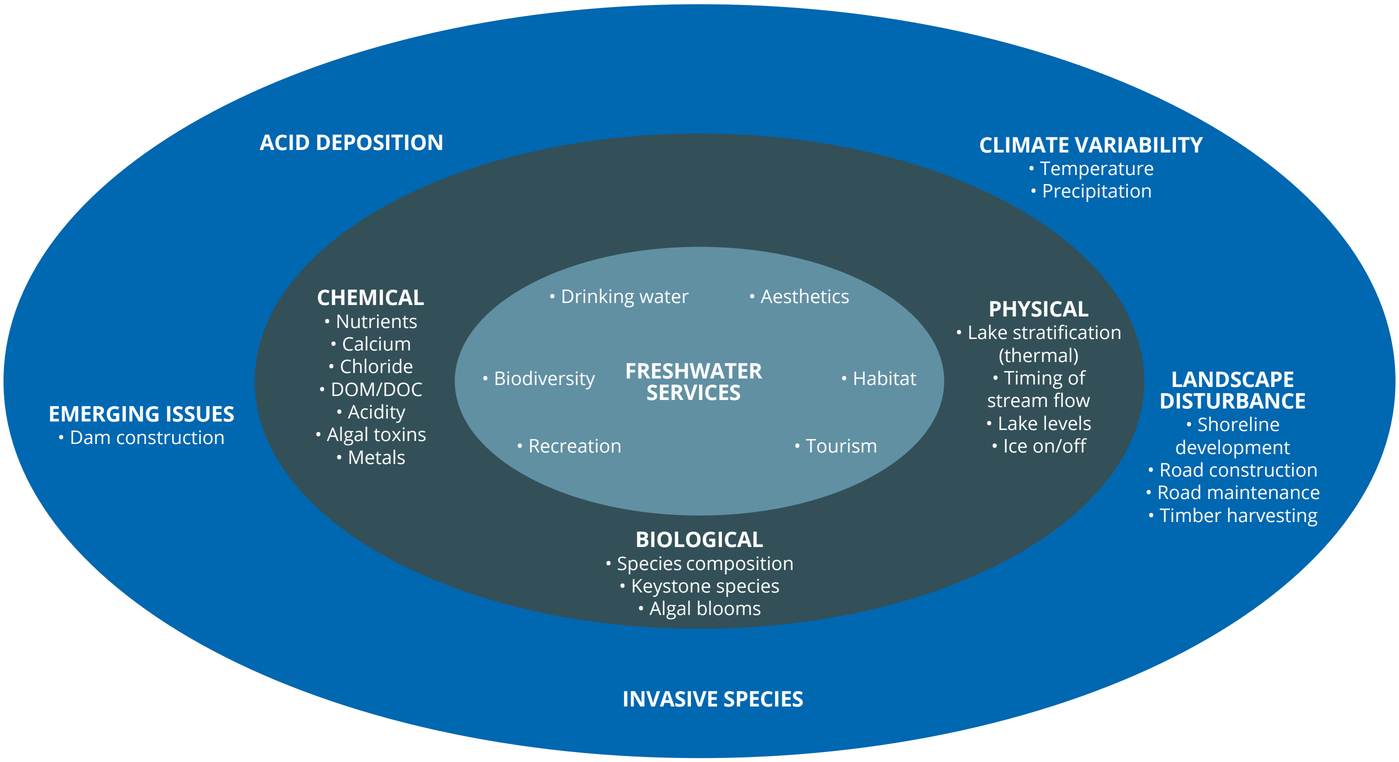

Figure 8: Freshwater services, cumulative effects and stressors operating at regional and local scales in the Muskoka River Watershed

Complex interactions among these stressors result in numerous cumulative effects. Key findings include the knowledge that warmer air temperatures promote water column stability and stimulate the growth of cyanobacteria in relatively shallow lakes with elevated phosphorus. Chloride derived from road salt is more toxic to aquatic animals that live in nutrient-poor lakes, which typify the watershed. The legacies of past acid rain and forest harvesting have lowered calcium levels in many Muskoka River Watershed lakes, which are approaching critical biological thresholds. Lakes in the Algonquin Highlands are most sensitive to further calcium declines.

Riparian forest disturbances, and particularly disturbances to treed wetlands, can cause pulses of phosphorus release to streams and lakes. Phosphorus levels in surface waters subsequently decline as watersheds recover from past disturbance events. Together, the cumulative effects of these stressors, and their complex interactions, will affect many services we harness from freshwaters within the watershed.

NEW TOOLS

Several assessment, biomonitoring and predictive/forecast modeling tools were developed to monitor and assess changes in stressors and cumulative effects within the watershed. The new tools developed include:

1. A soil and water assessment tool to assess cumulative effects of multiple stressors on the movement of water within the watershed. The calibrated model will be used to forecast seasonal stream flow and yield in the watershed for an upcoming report by the Muskoka Watershed Council focusing on the impacts of climate change in Muskoka.
2. Mathematical models to predict the abundance of cyanobacteria during warmer months in Three Mile Lake and Brandy Lake. Cyanobacteria (see example in Figure 9) are a type of algae that can produce toxins which are harmful to human health. The forecast models developed were specific for each lake and used nutrients, water column stability and wind speed as predictors. Data used in the models, such as lake temperature and water column stability, are expected to change over time in response to climate change.
3. Biological tools to track changes in lake condition resulting from stressors, using information regarding the presence and/or abundance of sensitive indicator organisms to measure biological condition and assess waterbody condition. Using benthic invertebrate survey data, normal ranges of benthic invertebrates were assessed and used to develop a biocriteria index by which waterbody condition can be assessed.
4. A diatom index (see an example of diatoms in Figure 9) for application to lakes in the Muskoka River Watershed. This biological tool is sensitive to low levels of stress and may serve as an early warning indicator of nearshore disturbances, which may not be adequately captured with current lake monitoring.

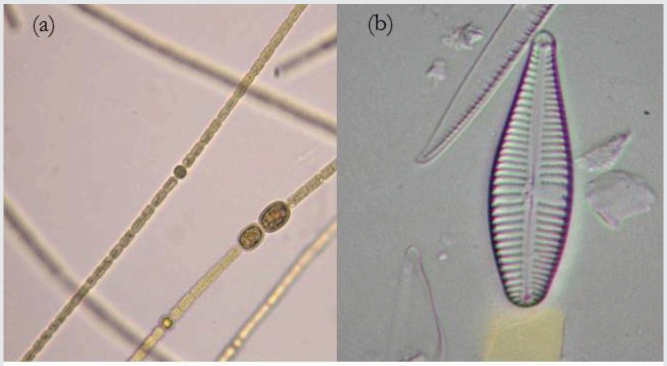

Photo by L. Hintsch *Photo by C. Hyatt*

Figure 9: Cyanobacteria (a) and Diatoms (b)

SUMMARY OF MUSKOKA WATERSHED MONITORING RECOMMENDATIONS			
PROJECT COMPONENT	**RECOMMENDATIONS FOR MONITORING**	**ADVANTAGES**	**LIMITATIONS**
Calcium and Logging	↗ Considering that timber harvesting in catchments of lakes with low calcium levels may cause calcium concentrations to drop below a biologically damaging threshold, future studies should be conducted to explore the long-term application of treatment options (e.g. wood ash) as a means to improve calcium levels in forest soil.	↗ Will facilitate site restoration and inform timber harvesting and planning.	↗ Longer-term, collaborative (with government and industry partners) experimental research is required to comprehensively explore all potential amendment options.
Chloride	↗ In light of the findings of chloride toxicity on aquatic herbivores, the Canadian Water Quality Guideline for chloride should be revised to consider the nutritional status of lakes. Further local guidelines for chloride should be developed to protect against ecological effects at the local scale. Specifically, the chloride toxicity threshold should be lower in lakes that are oligotrophic.	↗ Clearly demonstrates the importance of chloride and will allow us to account for toxicity within aquatic environments.	↗ Our knowledge of chloride is limited to these initial studies. There is need for further studies to assess the interactive effects of different chloride sources and their application rates.
Climate monitoring	↗ Existing meteorological stations in the watershed are primarily concentrated in the eastern/central portion of the watershed leading to large gaps in data for the north and southwest. ↗ There is need to establish one or two meteorological stations in the north and southwest.	↗ Increasing the number of weather stations would facilitate better characterization of weather patterns and variability within the watershed. ↗ An improved climate dataset would increase our ability to model and forecast climate and future hydrological changes in the watershed.	↗ Funding for the construction and operation of new weather stations may be limited.

SUMMARY OF MUSKOKA WATERSHED MONITORING RECOMMENDATIONS

PROJECT COMPONENT	RECOMMENDATIONS FOR MONITORING	ADVANTAGES	LIMITATIONS
Biological monitoring	↗ Biological monitoring programs should emphasize the use of benthic invertebrate indices that have been shown to distinguish reference from impacted communities. These indices should be interpreted relative to tabulated normal ranges. ↗ The information produced from application of the diatom index should be incorporated into the District of Muskoka's Watershed Report Card. This would provide decision makers and residents with additional information about the health of the nearshore environment of lakes within the Muskoka River Watershed.	↗ Provides an effect-based measure of ecosystem condition that is integrative of stressor exposures over time, sensitive to the combined effects of multiple stressors, and relevant to valued ecosystem components pertaining to the ecological condition of surface waters ↗ Indices that are sensitive to shoreline development and catchment land-use have been described. Numerical criteria for judging waterbody condition are available for these indicators, in the form of simple-to-use tables that describe normal ranges of index values observed among reference sites.	↗ Biological indicators are useful for measuring cumulative effects of multiple stressors, but have little ability to diagnose the particular stressors that are causing the biological response. Indicators are best when paired with stressor-based monitoring methods, such as water chemistry assessments ↗ Models attempting to predict biological index values explained a relatively small proportion of variation in community structure; therefore these indices are likely not suited for use in scenario-based models (i.e., for "future exercises" in cumulative effects assessment)
Expanded lake monitoring	↗ Currently, the majority of lakes (77%) in the watershed can be classified as reference lakes, as they are surrounded by watersheds with at least 90% of natural vegetation and have no associated dams or waste sites. In contrast, a smaller number of lakes (23%) in the watershed can be classified as impacted. The existing monitoring program run by the DMM should be updated to better represent the full range of lake types across the landscape. ↗ The current monitoring program samples only 5% of reference lakes, focusing mainly on lakes that are large, deep, at lower elevation and easy to access. ↗ There is need to increase the number of lakes monitored at higher elevation, and especially small, shallow lakes because they respond faster to changes in stressors. Emphasis should also be placed on sampling more lakes with elevated phosphorus concentrations, allowing for an improved understanding of ecological effects.	↗ An updated monitoring program will allow for better characterization of lakes across the watershed and allow DMM to optimize their aquatic ecosystem monitoring strategies. ↗ A modified sampling program will also inform future assessments of cumulative stressor effects.	↗ Not all of the lakes that are recommended for addition to the list of monitored lakes fall within the DMM boundary; consequently their monitoring will require collaboration with other end users in the watershed.
Cyanobacteria	↗ The forecast models developed for Brandy Lake and Three Mile Lake can be used to predict cyanobacteria abundance, allowing lake managers to notify the general public of possible exposure. ↗ For lakes that are prone to high levels of cyanobacteria, monitoring programs should collect information regarding lake temperature and chemical parameters on a biweekly basis to facilitate future development and refinement of forecast models.	↗ Forecast models are highly valuable for addressing public health issues and recreational use of lakes in the watershed.	↗ Considering that the predictive power of forecast models is dependent on length of the data set, model development for other lakes that are prone to cyanobacteria blooms will require data to be collected over multiple years.

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