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Environment Canada's Lake of the Woods Science Initiative 2008 to 2011 – Summary

Canada

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Environment Canada
Inquiry Centre
10 Wellington Street, 23rd Floor
Gatineau QC K1A 0H3
Telephone: 819-997-2800
Toll Free: 1-800-668-6767 (in Canada only)
Fax: 819-994-1412
TTY: 819-994-0736
Email: enviroinfo@ec.gc.ca

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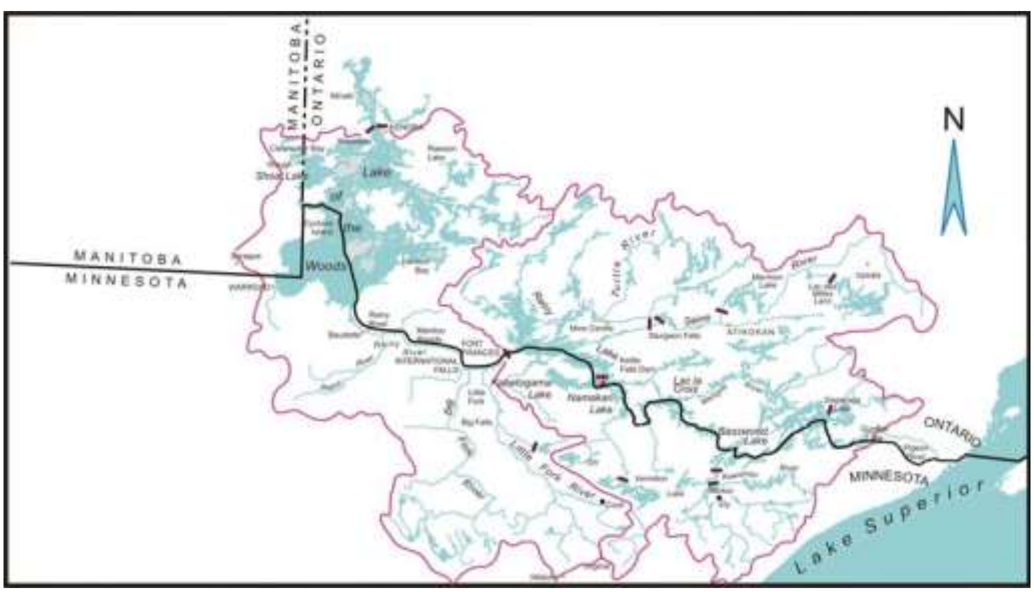
The Lake of the Woods is a large, transboundary water body located at the junction of the provinces of Ontario and Manitoba, and the U.S. state of Minnesota (Figure 1). Local and national concerns with noxious and potentially toxic cyanobacteria (aka blue-green algae) blooms and declining water quality in Lake of the Woods (LOW) prompted the formation of Environment Canada's Lake of the Woods Science Initiative in 2008 as part of a larger program to assess and remediate deteriorating water quality in Lake Winnipeg. The framework of the initiative was based on four key activities:

1. Scientific assessment of existing LOW hydrologic and water quality/nutrient databases, and overall scoping of the physical system;
2. Improved characterization of hydrological loading and physical limnology of LOW, in conjunction with the development of computer-based modelling of lake processes;
3. Improved estimation of overall LOW nutrient loading and nutrient budget; and
4. Improved characterization of biological community and assessment of risk and impairment by algal blooms.

This report summarizes the results of three years of Environment Canada's science and monitoring efforts in the LOW watershed. Our goals have been to address key knowledge gaps and increase our understanding about nutrient transport and cycling in LOW, and their role in the development of the blooms and the integrity of the lake. Some of the key results of this and other initiatives are presented here in this report. The report also identifies further data gaps and makes recommendations towards future work on the lake.

Map showing the Lake of the Woods and Rainy River basins (Detailed basin map)

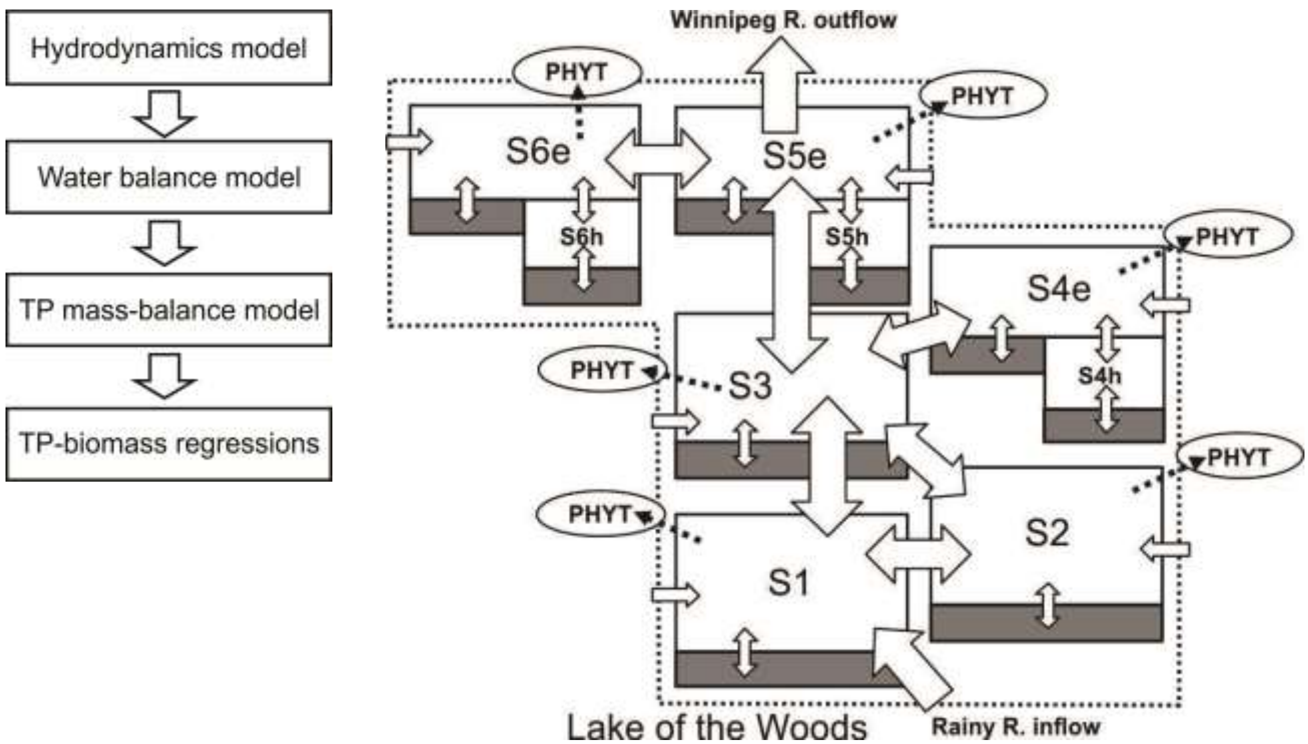


Hydrological Modelling

LOW is a spatially complex water body, with a large shallow, polymictic southern basin, and a series of interconnected northern sub-basins with numerous islands and deep, stratified bays. Physical processes play a dominant role in controlling material and nutrient loading, sequestration and export, and their effects on LOW water quality and biological productivity. Therefore, the development of a valid hydrodynamic model was fundamental to identify links between blooms and nutrient sources (natural and anthropogenic), and to develop effective monitoring and management programs.

As a first step, digital bathymetry data was derived for LOW from detailed navigational charts from the Canadian Hydrological Service. A modelling framework was then developed, and its suitability as a management tool for LOW evaluated. A numerical physical circulation model was first used to estimate exchange flows among different segments of LOW, based on the three-dimensional hydrodynamic Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). POM output was then linked to a dynamic water column–sediment exchange model to estimate Total Phosphorus (TP) levels across LOW. Finally, empirical relationships derived from among lake meta-analyses were then used to predict the algal community (e.g., chla, phytoplankton biomass and taxonomic composition) as a function of modelled TP concentrations.

The linked modelling framework provided reasonable simulations of current speed and direction, total phosphorus, and algal biomass, as validated from a limited number of field observations. Additional observations will provide more robust validation of the hydrodynamic and eutrophication models. This model framework will be used later to assess the water quality improvements resulting from anticipated nutrient management in the basin.



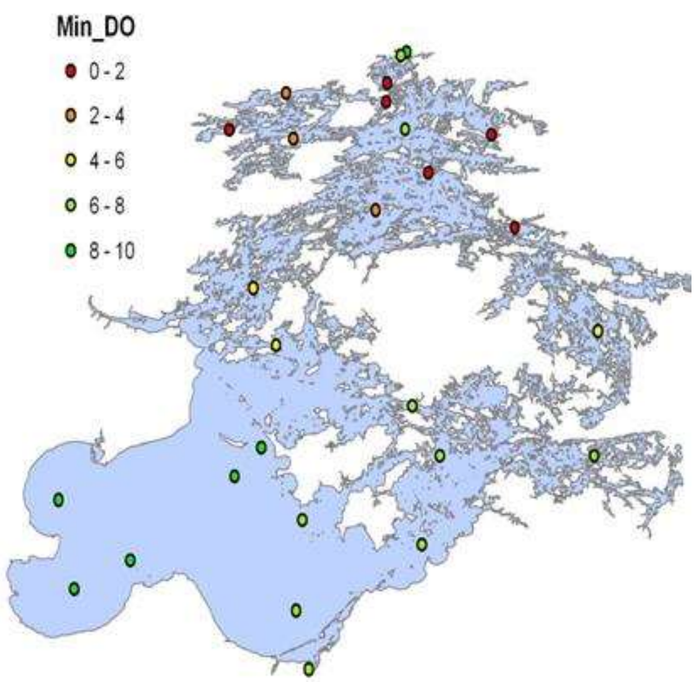
The schematic of model spatial network and TP mass flows in the LOW eutrophication models (e = epilimnion and h = hypolimnion). The hollow arrows indicate mass flows through the system. The dashed-line arrows indicate the empirical relationship between TP and phytoplankton (PHYT) biomass. The grey boxes represent the sediment layers.

Water Quality Monitoring

In 2008, Environment Canada developed a water quality monitoring program on LOW and the Rainy River, including the installation of precipitation samplers. Nutrients, major ions and mercury were monitored at four sites along the Rainy River. Major ion concentrations were reflective of the local geography and were negatively correlated with discharge rates. Total phosphorus in the Rainy River was moderate (0.013 to 0.059 mg/L), with a median concentration of 0.021 mg/L, but occasionally exceeded the International Joint Commission Rainy River Alert Level of 0.03 mg/L. Concentrations of nitrates/nitrites, ammonia and total nitrogen were low to moderate and did not exceed guidelines. Concentrations of phosphorus and ammonia in current-day samples (2009–2011) have declined significantly as compared with historical Environment Canada collections (1979–1985), reflecting improvements in water quality on the Rainy River in the later portion of the 20th century.

In general, water chemistry and physical limnology showed significant spatial heterogeneity throughout LOW. The large shallow basins in the southern portion of the lake were well mixed, while many of the deep, sheltered sub-basins in the north were thermally stratified in the summer, resulting in substantial declines in dissolved oxygen in the hypolimnion (Figure 3). Spatially, sites were arranged in three groups by water chemistry: Whitefish Bay in the northeast was characterized by low concentrations of ions and nutrients; Clear Water Bay and Poplar Bay in the northwest were characterized by higher concentrations of anions and cations and low to moderate nutrients; the main body of the lake was arranged along a north-to-south nutrient gradient, with concentrations of nutrients being highest in the south. Phosphorus concentrations in LOW generally typify a meso-eutrophic system (average 0.026–0.028 mg/L). Concentrations were significantly higher in the south, where phosphorus was primarily in particulate form, although high concentrations of dissolved phosphorus were measured in the hypolimnion of northern basins.

Minimum dissolved oxygen (DO) mg/L concentrations in LOW in bottom waters during summer and fall.



Inorganic precipitation samplers were located at three sites in the LOW basin: 1) Kenora, Ontario; 2) Sioux Narrows, Ontario; and 3) Buffalo Point, Manitoba, to quantify nutrient loads from wet precipitation and to examine geographic variation in loadings. Total nitrogen from wet deposition was estimated to be 298 tonnes per year and was consistent across the basin. Total phosphorus loading was 31 t on average, but with considerable geographic variation; phosphorus load estimates were twice as high in Kenora and Buffalo Point compared with Sioux Narrows. Our nutrient load estimates from wet deposition are approximately half of that estimated from long-term precipitation data at the Experimental Lakes Area, which includes both wet and dry deposition.

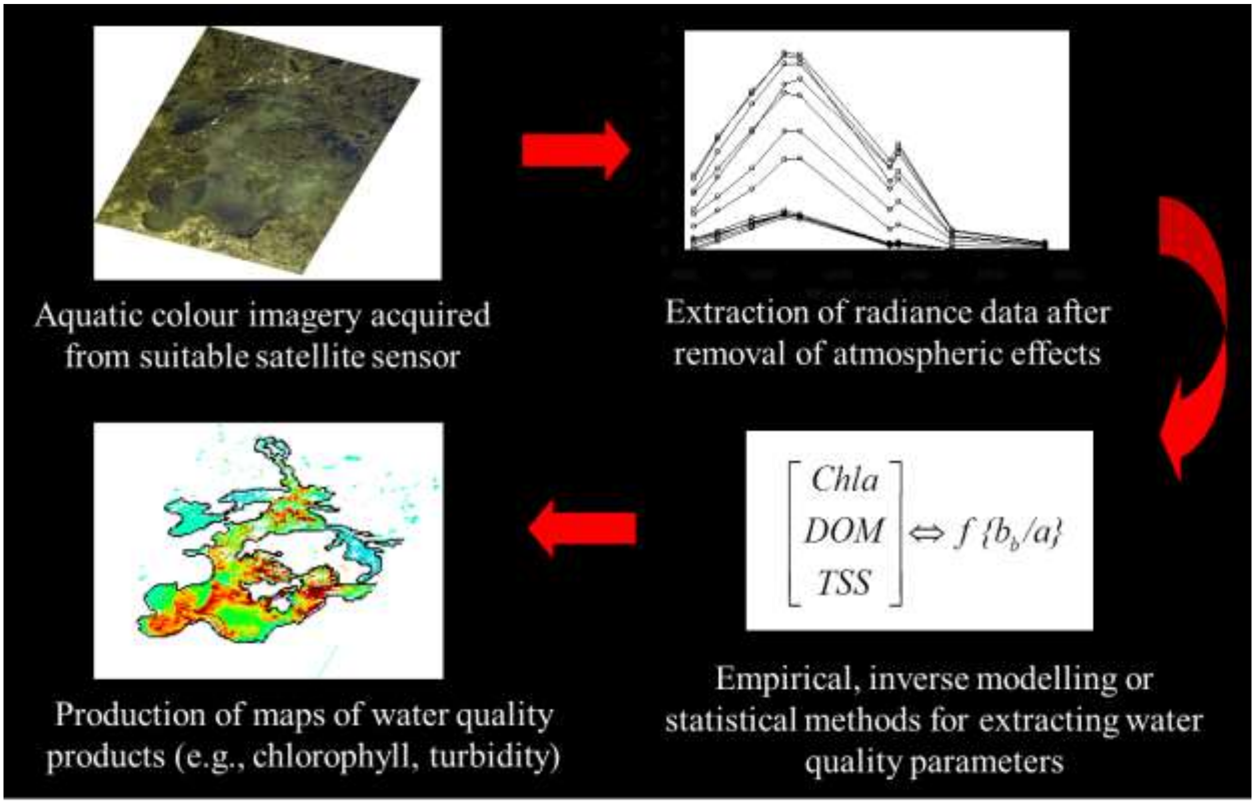
Mercury concentrations in the Rainy River were similar to those reported elsewhere within the watershed, with average annual concentrations ranging from 1.10–3.16 ng/L and rarely exceeding the Rainy River Alert Level of 6.9 ng/L. Although mercury concentrations were below guideline levels, there is still a general desire for a reduction in mercury concentrations in water and sediments because of its bioaccumulation in the food web, particularly as concerns body burdens in sport fish. Pesticides (organophosphates, neutral herbicides, phenoxy acid herbicides, sulfonyl urea herbicides and glyphosate) were sampled at eight stations on LOW in 2009 and 2010. Analytical results indicate that few pesticides were present in LOW surface waters, and those detected were found at low concentrations far below toxicity threshold.

Satellite Monitoring of Algal Blooms

In 2009, Environment Canada initiated a study to determine the feasibility of utilizing aquatic colour remote-sensing methods to monitor algal blooms on LOW using the European Space Agency's MERIS aquatic colour sensor. MERIS imagery and in-situ observations of water quality parameters and their associated optical properties were obtained during the fall of 2009, capturing the onset and progress of an intense cyanobacteria bloom.

In-situ measurements confirmed LOW to be optically complex; waters are shallow and highly turbid, with Secchi depths as little as 0.3 m, very high dissolved organic matter resulting in strong light attenuation and intense cyanobacteria blooms causing surface scum accumulations. The MERIS derived Maximum Chlorophyll Index (measure of the chlorophyll-related enhanced water leaving radiance) accurately depicted the location and extent of the cyanobacterial bloom and was strongly correlated with in-situ chlorophyll concentrations.

There was a progression in bloom activity from an early, intense and prolonged bloom in the southern, western and central zones of LOW to a later, less intense and shorter bloom in the northern portions of the lake, with eastern sections (Whitefish Bay) exhibiting no notable bloom activity for the entire period. These observations are consistent with two nutrient loading scenarios: (1) nutrient loadings predominantly from the Rainy River, which leads to high phosphorus and nitrogen concentrations throughout the southern part of the lake, with moderate concentrations in the north-central zones and low concentrations at sites away from the main south-north flow of water (DeSellas *et al.*, 2009); and (2) internal loading from the southern basin providing a seasonal burst of nutrients to stimulate blooms.



Step 1: Aquatic colour imagery acquired from suitable satellite sensor.
Step 2: Extraction of radiance data after removal of atmospheric effects.
Step 3: Production of maps of water quality products (e.g., chlorophyll, turbidity).
Step 4: Empirical, inverse modelling or statistical methods for extracting water quality parameters.

Concerns have been raised in recent years over increasing occurrence and intensity of algal blooms on the lake. Multi-year image analysis (2003–2009) did not show any discernible increase in bloom intensity over the seven-year time period. However, there was evidence of intense bloom activity during dry, warm years, with a suggestion of blooms occurring later each year.

Benthic Monitoring

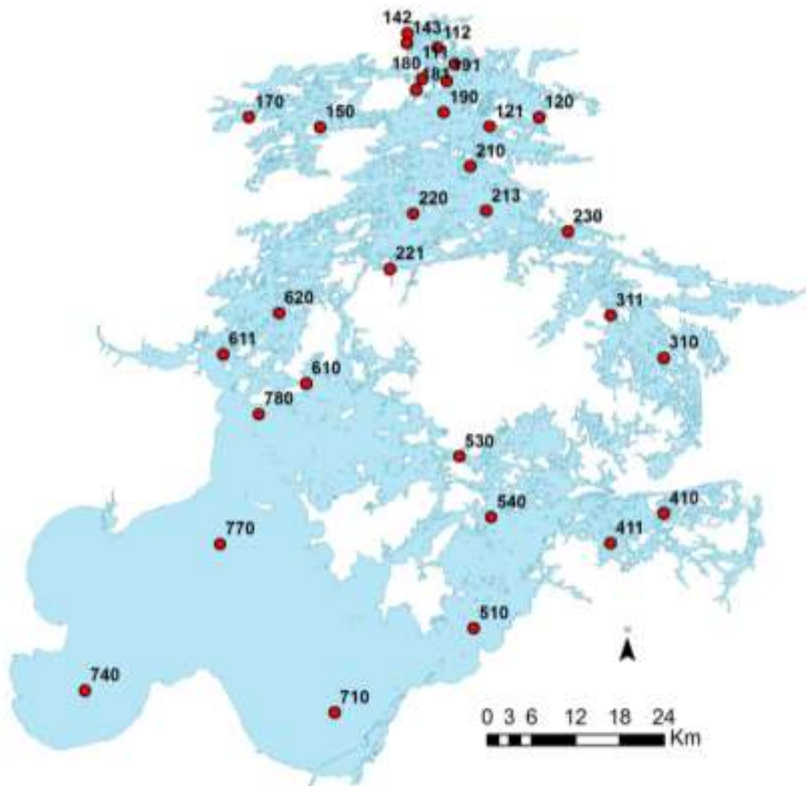
Sediments act as an important sink for many of the compounds entering the LOW basin. Surficial sediments were sampled at 31 stations on LOW using a mini-box core and analyzed for physical and chemical characteristics. Legacy organic contaminants, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) were below the detection limit in sediments of LOW. In contrast, the majority of sites exceeded provincial lowest effect levels (LEL) for the protection of the benthic ecosystem for chromium, copper, manganese and nickel, with some sites also exceeding LELs for lead and arsenic. Elevated metals in the sediments may be the result of weathering of ore-bearing rocks but in some cases may also be related to past mining activities in LOW, particularly the gold mining boom at the beginning of the 20th century. Sediment nutrient concentrations were also elevated.

Total Kjeldahl nitrogen (TKN) concentrations exceeded provincial severe effect levels (SEL) at the majority of sites, while total phosphorus concentrations (P total) exceeded provincial LELs at all sites and SELs at some sites. It has been hypothesized that high phosphorus concentrations in the sediments act as a source of internal loading in LOW and may stimulate algal blooms.

The sediments and overlying water layers are home to an important biological community. Within this community, macro invertebrates were monitored as an indicator organism of ecosystem health. Overall benthic invertebrate diversity was low, and was positively correlated with dissolved oxygen, chlorophyll, pH and temperature, and negatively correlated with sediment nutrients and metals.

The collection of benthic invertebrates using the Canadian Biomonitoring Network (CABIN) approach is being used to develop a benthic reference model for LOW. While this work is still ongoing, three major groups of reference sites were identified based on habitat and taxonomic similarity. These were used to evaluate test sites for comparison with the benthic community. Two sites, one in Poplar Bay and one in Big Stone Bay, were identified as impaired, with substantial reductions in diversity. In the future, the CABIN reference model may be used to assess new test sites against the known reference model as well as providing baseline data of the current benthic community structure for the examination of temporal trends.

This figure shows the locations of benthic sampling stations on LOW from 2008 to 2010. The inset shows stations in the northern basin of the lake near Kenora, Ontario. Environment Canada's CABIN approach was used to characterize the benthic community.



Algal Communities: Relationships between physicochemical regimes, taxa and toxins

LOW fits within the mid-range (meso-eutrophic) of north temperate lakes in terms of total phosphorus-algal biomass relationships, although there is significant variance in biomass for any given level of total phosphorus.

In general, spring samples are dominated by a low biomass of diatoms or other eukaryotic taxa. As seen in previous studies, the predominant species causing the widespread late summer/fall blooms are N2-fixing cyanobacteria, most of which (*Aphanizomenon flos aquae* complex) are not known to be toxic. Although mixed layer samples may contain low toxin levels, these may become greatly concentrated, for example during calm conditions when buoyancy-regulating cyanobacteria can form surface scums. These surface blooms can be transported towards inshore areas by wind and water circulation and represent a significant risk to these areas.

There was a strong south-north increase in PEr-rich picocyanobacteria, and while PCy-rich picocyanobacteria were generally more abundant, they showed no distinct south-north spatial patterns. PE abundance appears to be most strongly affected by non-nutrient constraint such as transparency and spectral attenuation, while PC and eukaryotic picoplankton may be affected by both light and nutrients. Overall, bacterial abundance is higher than that of autotrophic picoplankton. The few data available suggest that bacteria numbers are not directly derived from the Rainy River inflow and show a strong seasonality in both autotrophic picoplankton (APP) and heterotrophic picoplankton (HPP) abundance, which peak mid- or late summer.

While there was much variation in deficiency indicators, the body of evidence suggests that while phosphorus is ultimately limiting over a broader time scale, shorter-term deficiencies in other limiting resources are likely to occur. Overall, the results suggest: i) higher overall phosphorus deficiency in the northern segments and a general across-lake increase in phosphorus deficiency in mid- to late summer; ii) seasonal changes in phosphorus and nitrogen deficiency and the possibility of co-limitation in late summer and fall with increases in nitrogen-fixers; and iii) a strong link between low silica levels and plankton deficiency, especially in the early season in southern sectors, and later in the season in northern zones.

Conclusions and Recommendations

Local and national concerns with noxious and potentially toxic cyanobacteria (aka blue-green algae) blooms and declining water quality in LOW prompted the formation of Environment Canada's Lake of the Woods Science Initiative in 2008 as part of a larger program to assess and remediate deteriorating water quality in Lake Winnipeg. Our goals have been to address key knowledge gaps and increase our understanding about nutrient transport and cycling in LOW, and their role in the development of the blooms and the integrity of the lake. This will assist in generating basic understanding of the ecology of this lake and ensure that resource management decisions lead to its long term sustainability

Environment Canada has been working in LOW over the past three years with binational, provincial, regional and local partners to develop a science-based nutrient and bloom management program within a viable socio-economic framework, based on ecologically relevant targets and building upon work and expertise already in place. Some of the key results of this and other initiatives are presented annually at the International Lake of the Woods Water Quality Forums in International Falls, the primary professional gathering for scientists and resource managers working in the LOW and Rainy River basins.

Environment Canada has partnered in a number of different LOW projects, aimed at increasing our ability to predict and manage blooms and other water quality issues in this complex water body. LOW includes a large shallow mixed southern basin, and a highly complex series of northern sub-basins with numerous islands and some deep, stratified bays. This complexity and significant difference in the basin composition (glacial-shield) and water chemistry makes it extremely difficult to develop an integrated understanding and management approach to this system. The vast size and complexity of this system makes it difficult to develop and implement practical, economically feasible and effective monitoring and management programs, and Environment Canada has been at the forefront of efforts to develop and validate tools to overcome these issues using a multi-scale approach. Our large-scale projects have included remote sensing and whole-lake models that couple physical-chemical and biological elements to predict nutrient levels and associated risk of algal blooms in this multi-basin water body. In conjunction with this, a remote-sensing capacity has been developed as a tool to map and analyze the severity, composition and temporal-spatial dynamics of the blooms in this lake on a seasonal and long-term basis. At a finer scale, water quality samples have been collected at sampling locations throughout all major basins in LOW to evaluate the inputs and distribution of nutrients and other factors that determine the frequency, severity and spatial-temporal patterns of the blooms and their toxigenicity. Finally, different elements of the lower aquatic foodweb have been examined (micro grazers, bottom fauna and algae including cyanobacteria) to help gauge their responses to physical and chemical characteristics of their environment. Water quality data and physical limnology data being collected by this work are also contributing to nutrient models for LOW, both by collaborators in Environment Canada as well as by partner agencies such as the Ontario Ministry of the Environment and the Minnesota Pollution Control Agency.

The LOW monitoring initiative was initially guided by a need to address knowledge gaps that had been identified as limitations to understanding the nutrient issues in the basin. Since work began, the program has begun to provide information for several key issues in the basin. Currently, information from LOW water quality monitoring is contributing to a better understanding of nutrient-loading sequestration estimates for the Winnipeg River, the main outflow of the lake. Nutrient-related issues in LOW are also very similar to those in Lake Winnipeg, and knowledge learned in one location will be directly transferable to the other. Finally, the International Multi-Agency Working Arrangement (IMAWA) is working to establish nutrient-loading targets for LOW, and ongoing monitoring will inform that decision-making process as well as provide a foundation for tracking the effectiveness of those decisions. We recommend the development of a long-term water quality monitoring program for LOW, in collaboration with other IMAWA members. Currently, the monitoring program can aid decision makers by supplying information on in-lake concentrations, and nutrient loadings through both direct measures as well as through advanced modelling and assessment. However, long-term water quality data will be needed for improving nutrient loading estimates, which would provide decision makers with a more complete picture of nutrient issues in the basin.

Current nutrient models rely on estimates of aerial deposition from the Experimental Lakes Area, rather than from within the LOW basin itself. The Experimental Lakes Area data are valuable as they provide a long-term estimate of aerial deposition and include both the wet and dry components. While the data from our three Environment Canada wet precipitation samplers are limited to a shorter time period and include only wet precipitation, they point to a significant spatial variation in phosphorus concentrations in wet precipitation that would not be captured by a sampler in a single location. Presently, our three wet precipitation samplers within the basin have been withdrawn. Continued monitoring of nutrient inputs from aerial deposition within the LOW basin is recommended to more thoroughly characterize this component of the nutrient budget.

While preliminary modelling of lake behavior has been conducted, additional data exploration and final modelling will require continued support. There are a number of data gaps that have not been addressed in these first three years of sampling. Temporal analysis of the basin needs to be expanded to further understand nutrient cycling and its effect on phytoplankton species in the lake.

A potential nutrient source for LOW, near-shore loading as a result of cottages and other development, is not clearly understood and has not been addressed with current efforts. Preliminary estimates of septic/sewage inputs from the lake suggest that while they may be a relatively minor portion of the total nutrient budget for LOW, in bays with shoreline development, they may be a significant contributor to nutrient loading (Hargan *et al.*, 2011). An investigation to determine the impacts of nutrient inputs in bays with extensive cottage development on local water quality conditions and biota may be of interest, particularly in bays that have been identified as important fish nurseries.

Nutrient and mercury levels from the Rainy River to LOW should continue to be monitored. The Rainy River is the dominant source of nutrients into LOW. Efforts to refine the nutrient budget, and in the future to reduce loadings, will be reliant on continued monitoring of this important source. Routine sampling on the Rainy River has been addressed through contracts with local collectors, but could not continue without additional funding. In the future, it is possible that mitigation and compliance efforts may shift the focus to load-based monitoring. In order to estimate loadings from the Rainy River to LOW, discharge data from near the mouth of the Rainy River is required. This data is currently being developed at a temporary gauge at Wheelers Point, Minnesota. Although the gauge resides in the U.S., we note that data from this gauge is beneficial to our monitoring program.

Algal blooms continue to be a major concern with local stakeholders and management, with potential for toxins and severe impacts on water quality, recreational and tourist industries, and property value. The prevailing model is that the blooms originate in the south and move up towards the north basins; however, there is evidence to suggest that these are separate populations that arise independently in response to local nutrient input and lake-wide processes. This is an important question, since it has implications for tracking and controlling the causes of these blooms (i.e., local and across-basin), predicting and managing the risk of toxins, and developing valid nutrient-biomass management models. To address this key issue and resolve among different plankton populations requires a multi-year study using a combination of taxonomic and molecular methods along with physical modelling, water quality measures and remote sensing.

Although mixed layer samples may contain low toxin levels, these may become greatly concentrated, for example during calm conditions when buoyancy-regulating cyanobacteria can form surface scums. It is likely that there are several sources of toxins in LOW, which vary among seasons and basins, and that could be resolved using more focused physiological and molecular approaches to provide important insight into the prediction and management of toxins in LOW. Some of the cyanobacteria identified in this lake have been reported as producers of other cyanobacteria toxins (anatoxin-a, saxitoxin), but to date, these have not been measured for LOW, and it is recommended that these toxins be also addressed in future studies.

From an earth observation perspective, there has been significant progress in the area of algal bloom monitoring from satellite remote sensing, with methods validated and clearly demonstrated as valuable to LOW monitoring activities. Remote-sensing technologies offer not only the ability to identify and assess impacts on a basin-wide scale, but may also provide much-needed historical data with regard to nutrient impacts. Further work is required to make such image processing and analysis available to the user community on an operational basis. Additional effort is required from an R&D perspective in order to: (1) further develop methods to discriminate algal bloom composition (with particular interest in potentially harmful cyanobacteria); (2) investigate further the effects of variable algal depth distributions on remote sensing signals; (3) determine the effect of variable light quality (spectral and intensity) on algal growth; and (4) investigate further the role of physical processes on algal bloom dynamics on the lake.

Finally, significant work is left to be done in relation to issues regarding sediment in LOW. Benthic invertebrates are currently being used as biological indicators of water and sediment quality in LOW through the CABIN program. At this time, we do not have a sufficient data set to adequately build a reference model to characterize the benthic invertebrate community of LOW and detect impairments to this community. Enhanced spatial coverage of the lake is required, particularly in the shallow, productive zones of the lake. Sediment sampling is also being used to address concerns in the basin regarding internal loading of phosphorus as a driver for algal blooms www.**ec.gc**.ca

Additional information can be obtained at:

Environment Canada
Inquiry Centre
10 Wellington Street, 23rd Floor
Gatineau QC K1A 0H3
Telephone: 1-800-668-6767 (in Canada only) or 819-997-2800
Fax: 819-994-1412
TTY: 819-994-0736
Email: enviroinfo@ec.gc.ca