

1 **Advances in eutrophication science within Lake of the Woods, a complex transboundary lake - forward to the**  
2 **special section**

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15

16 **Abstract**

17 Outside of the five Great Lakes, Lake of the Woods (LoW) is the largest transboundary lake shared by Canada  
18 and the United States. Over the last two decades, an international consortium of researchers has advanced our  
19 understanding of eutrophication science in this complex watershed. This introductory paper outlines eleven  
20 research articles included in this special section, within three main themes pertinent to LoW: external  
21 phosphorus sources to LoW and internal phosphorus loading, lake and watershed modeling, and new insights  
22 into cyanobacterial and harmful algal blooms (cHABs). We conclude with a roadmap to guide future  
23 transboundary water quality management in LoW, including remaining research gaps and future monitoring  
24 needs.

25

26 **Keywords: Lake of the Woods, nutrients, harmful algal blooms, transboundary**

27

28 **Introduction**

29 Lake of the Woods (LoW; Figure 1) covers 4,350 km<sup>2</sup> along the international border between Canada and  
30 the United States and is a focal point within a current and historically significant landscape. LoW, and other large  
31 upstream lakes, provide important ecosystem services, including drinking water for over 750,000 people and a  
32 robust tourist industry, principally sport fishing and water-based recreation. This hydrologically complex lake,  
33 which drains over 70,000 km<sup>2</sup> of primarily forest, wetlands, and water (Figure 1), frequently develops  
34 cyanobacterial and harmful algal blooms (cHABs), especially in the shallower and more eutrophic southern  
35 basins. Over the last two decades an international consortium of government agencies, Tribal and First Nations  
36 and Métis partners, academic researchers, citizen volunteers, and non-governmental organizations has  
37 advanced eutrophication science and cHABs public awareness (Anderson et al., 2017; Clark et al., 2022). In 2008,  
38 the Minnesota Pollution Control Agency (MPCA) declared the Minnesota waters of LoW impaired for aquatic  
39 recreation due to exceedances of regional eutrophication criteria (Heiskary and Wilson, 2008) for phosphorus,  
40 chlorophyll-a, and water clarity. In-lake phosphorus was shown to be key in limiting phytoplankton biomass in  
41 LoW while short-term nitrogen and silica deficiencies influence the phytoplankton community composition  
42 (Watson and Kling, 2017). The US EPA approved a Total Maximum Daily Load (TMDL) Study in 2021 after a  
43 decade of monitoring and in-lake and watershed modeling. Briefly, a total phosphorus (TP) reduction of 140  
44 metric tons, or 17.4 % of the LoW's annual phosphorus budget, is deemed necessary to attain the 30 µg/L  
45 summer (June – September) average TP standard in Minnesota's LoW waters (MPCA, 2021). In 2016,  
46 Environment and Climate Change Canada (ECCC) launched a four-year intensive science effort to develop  
47 research, modeling, and monitoring to determine the level of nutrient reductions required to achieve water  
48 quality improvements (ECCC, 2021). ECCC completed this work in 2020, in collaboration with partners. The  
49 results were used to inform a proposed set of lake ecosystem objectives and phosphorus reduction scenarios for  
50 input from the public, Indigenous peoples, non-governmental organizations, municipalities and local businesses  
51 (Rokitnickiwojcik, 2021). Both of these efforts were aided by a change in watershed governance guided by the

52 International Joint Commission (IJC). In 2013, the IJC created the International Rainy – Lake of the Woods  
53 Watershed Board with a mandate to monitor and report on the ecological health of the aquatic ecosystem (IJC,  
54 2012). Subsequently, the IJC published a Water Quality Plan of Study (IJC, 2015) with specific projects to improve  
55 understanding of the basin’s ecosystem and support a balanced, binational approach to water quality  
56 management.

57  
58 Knowledge of the region’s environmental setting and history (Benidickson, 2019; Strube and Thomas, 2021) are  
59 necessary to guide present-day research and water quality management. For example, the climate of the Rainy-  
60 Lake of the Woods region is continental but is adjacent to two ecotonal boundaries – the deciduous forest-  
61 boreal forest ecotone and the prairie-forest ecotone (Ruhland et al., 2018) – and thus the region is a particularly  
62 sensitive area for tracking the limnological effects of past changes in climate (Frelich and Reich, 2010) and is  
63 expected to experience future climate-driven changes (Edlund et al., 2017b). Climate trends in the LoW region  
64 over the past three decades (MN DNR, 2022) show warmer winter and spring air temperatures (Greenwood and  
65 Eimers, this issue), slightly warmer and less windy summers, and increasing precipitation. Northern basins have  
66 seen significant declines in ice cover duration since the 1960s (Ruhland et al., 2010), but minimal changes in ice  
67 cover have been seen in the expansive southern basins (Reavie et al., 2017). Changes in these climatic factors  
68 affect lake thermal conditions, the timing of internal and external loading of nutrients (Macgillivray et al., this  
69 issue; Greenwood and Eimers, this issue), and phytoplankton seasonality and production (Ruhland et al., 2010;  
70 Edlund et al., 2017b; Paterson et al., 2017). The southern basins of LoW are known to be productive, with  
71 historical accounts of cHABs recorded during the fur trade and exploration era, decades before European  
72 settlement began in the late 19<sup>th</sup> century (Anderson et al., 2017). Paleolimnological records from throughout  
73 the southern basin record a long-history of cHABs in LoW, but with the highest concentrations of bloom  
74 indicators (fossil pigments) recorded in the mid-20<sup>th</sup> century, as well as a shift in bloom-forming species in more  
75 recent decades (Reavie et al., 2017, Edlund et al., 2017a). In contrast, the cyanobacterial toxin microcystin  
76 appeared relatively recently based on paleolimnological evidence (early 2000’s; Zastepa et al., 2017a; Pilon et  
77 al., 2019). Microcystin concentrations in surface waters remain relatively low partly because much of the bloom  
78 biomass is composed of *Aphanizomenon* which is not known to produce microcystin. However, microcystin  
79 concentrations become elevated when cHABs accumulate, especially along shorelines (Zastepa et al., 2017b).

80  
81 LoW’s principal tributary, the Rainy River, provides the majority of water and external nutrients to the lake. This  
82 river was severely degraded by industrial and municipal wastewater from about 1910 through the 1970s (IJC,  
83 1918, 1965, 1970); phosphorus loads to the Rainy River have declined dramatically in recent decades due to  
84 mandated improvements in wastewater treatment by both countries (Hargan et al., 2011). The river is now a  
85 high quality, valued resource with stable TP concentrations near 35 µg/L for most of the open water season  
86 (MPCA, 2020) although certain tributaries contribute disproportionately higher TP loads (Ellison et al., 2014;  
87 Macgillivray et al., this issue), and TP concentrations increase along its course from the Rainy Lake outflow to

88 LoW. Remote sensing of LoW indicates that cHABs have declined in intensity since 2003 (Binding et al., 2021;  
89 Binding et al., this issue), possibly in response to historical nutrient reductions in the Rainy River (Hargan et al.,  
90 2011; Edlund et al., 2017a). However, as noted above, the occurrence of the cyanobacterial toxin microcystin  
91 appears to be a relatively recent phenomenon (early 2000's; Zastepa et al., 2017a). Moreover, remote sensing  
92 research in LoW indicates that hot, dry summers have higher phytoplankton production, while cooler summers  
93 have the least intense blooms (Binding et al., 2011). Finally, there is a long and well-established history of  
94 international cooperation and collaboration on water issues in the Rainy-LoW basin. For example, water levels  
95 and outflows in LoW, and other upstream lakes, are well-monitored and have been regulated by the IJC since  
96 the early 20<sup>th</sup> century, balancing occasionally conflicting water uses, such as power production, flood control,  
97 and protecting aquatic life. Together our knowledge of these historical and modern conditions in LoW and its  
98 watershed are guiding research, monitoring, and management efforts to support a sustainable future and sound  
99 resource management for this multijurisdictional watershed.

100

### 101 **Overview of papers in this special section**

102

103 The eleven papers in this Special Section are summarized here by three main themes pertinent to  
104 eutrophication science in the LoW basin: external P sources to LoW and internal P loading, lake and watershed  
105 modeling, and new insights into cHABs. An additional theme of climate change is woven through all of the other  
106 themes.

107

108 Macgillivray et al. (this issue) found concentrations of TP and total suspended solids are strongly correlated in  
109 Ontario watersheds with comparatively high agricultural use, and increasing concentrations of TP and iron  
110 during periods of low-flow are suggestive of internal release via redox processes. These summer anoxic periods  
111 could 'seed' downstream cHABs. The strong hydro-climatic sensitivity of TP they observed indicates that  
112 frequent, multi-year monitoring efforts are needed to understand mechanisms of phosphorus delivery to LoW.  
113 Greenwood and Eimers (this issue) describe hydrologic variability across Ontario streams within the LoW basin,  
114 focusing on nutrient export in two distinct geologies (Figure 1) with similar precipitation, temperature, and  
115 runoff. Lake Agassiz basin streams are flashy with greater variability and strong seasonality in nutrient export  
116 that requires greater sampling effort to capture. Both stream flow and nutrient export in the Agassiz zone are  
117 especially sensitive to climate shifts. In contrast, watersheds on the Precambrian Shield respond more slowly to  
118 precipitation events and are less seasonally variable, likely due to the moderating effect of lake storage, which  
119 provides some 'buffering' to climate shifts. Trend analysis showed general warming and a shift toward more  
120 rainfall during the ice-covered months and earlier snowmelt. Eimers et al. (this issue) measured TP and nitrogen  
121 bulk atmospheric deposition to the LoW Basin. Phosphorus deposition was highly variable both spatially and  
122 seasonally, with the majority occurring in spring and summer, likely associated with local biogenic input.  
123 Nitrogen deposition was spatially variable and unrelated to landcover. The fraction of inorganic nitrogen that is

124 ammonium doubled, likely due to increases in agricultural sources upwind of the basin. Past TP models for LoW  
125 used a single annual P estimate from atmospheric sources; Eimers et al. (this issue) suggest this is not  
126 appropriate as winter deposition is much lower than past estimates, whereas non-winter deposition is  
127 substantially higher, and could be an important, unrecognized source of bioavailable P to nearshore waters  
128 during the growing season. Reid et al. (this issue) analyzed lower water column redox-sensitive and bio-relevant  
129 micronutrients aluminum, iron, and manganese to assess spatial and seasonal variability in LoW, and to better  
130 delineate potential drivers of eutrophication and cHABs. A unique signature of redox-sensitive metals was  
131 observed above the lakebed, with significantly different micronutrient signatures between locations that were  
132 on versus off the Precambrian Shield. Correlations between the bio-relevant element vanadium (an important  
133 element used in nitrogen fixation) and chlorophyll-a provide insight into potential elemental drivers of cHAB  
134 ecology in LoW.

135  
136 Four papers present results of ECCC's LoW integrated modeling framework efforts in support of their Science  
137 Plan. The ECCC integrated modelling framework consists of three main parts: (i) a transboundary LoW  
138 watershed model, which uses the Canadian version of the Soil and Water Assessment Tool (CanSWAT) model to  
139 study riverine inflows to LoW (Fong et al., this issue); (ii) a lake hydrodynamic model (AEM3D) to study seasonal  
140 transport, mixing, surface seiches, riverine plumes, water temperature and retention time (Valipour et al., this  
141 issue); and (iii) a biogeochemical model, which is coupled with the hydrodynamic model, to study nutrient  
142 redistributions and algae spatial and temporal distributions in LoW to predict the lake's response to the  
143 implementation of possible nutrient management strategies (Rao et al., this issue). The integrated modeling  
144 framework also includes a study examining the wind variability over LoW using a wind variability index to  
145 measure spread in wind direction and quantify lake-wide wind variability (Brunet et al., this issue). Brunet et al.  
146 show that directional variability in LoW depends on wind speed, with higher variability at lower speeds;  
147 variability was most pronounced in spring and fall. Their analysis indicated that geographically variable wind can  
148 be grouped into three LoW regions to represent the predominant wind directions accurately; they also show a  
149 need for a new meteorological station in the southeast basin of LoW. This will improve water quality  
150 management and future mechanistic ecological models because wind is a key driver of water circulation,  
151 transport, and lake mixing. Fong et al. (this issue) evaluated streamflow and spatial and temporal variability of  
152 nutrient fluxes in the LoW watershed using the CanSWAT model. The Rainy River was estimated to contribute  
153 88% of the external TP load to LoW, with most originating from non-point sources. Approximately 59% and 41%  
154 of the Rainy River TP originated in the U.S. and Canada, respectively. Estimated TP loads varied seasonally with  
155 over approximately 60% of the annual load occurring during the spring period (March to May). Annual TP loads  
156 varied from year to year partially because of differences in precipitation amounts and temperatures. Model  
157 results show that larger TP loadings tend to occur during periods of high precipitation. TP varied spatially across  
158 the LoW watershed, and the estimated TP yields tend to be lower in areas upstream of Rainy Lake and in regions  
159 around LoW within the Precambrian Shield, where more natural land cover is dominant. TP yields were generally

160 higher in regions downstream of Rainy Lake in the Agassiz zone, which has more agricultural land-cover.  
161 Valipour et al. (this issue) developed a high-resolution, three-dimensional model of LoW to study surface  
162 seiches, lake circulation, and water temperature. The predominant physical processes in LoW are surface  
163 seiches; wind and rivers drive mean lake-wide circulation and mixing. Main water circulation paths are to the  
164 northeast. Sabaskong Bay experiences warmer summer water temperatures with unidirectional mean flows to  
165 the lake. The spatial distribution of surface seiches show that responses to wind may be limited to one sub-  
166 basin; however, lake-wide responses were also observed, which suggests the seiche-induced oscillatory  
167 velocities can impact the transport paths. Modeled conservative tracers, consistent with observations, show  
168 that the Rainy River plume extent covers Big Traverse, Morson, and Little Traverse Bays. The retention time  
169 results suggest that residence/flushing times vary in different parts of the lake. The southern bays can be flushed  
170 within a season - in contrast to the nutrients in the isolated/northern bays, which may be derived mostly from  
171 either sediment and/or preceding seasons' loading. Rao et al. (this issue) present the development of a three-  
172 dimensional coupled hydrodynamic ecological model for LoW to assess the impact of nutrient inputs on the  
173 lake's ecological processes. The calibrated model explored the potential for the spatial and temporal status of  
174 ecological conditions of LoW, including its response to nutrient load reductions. Based on a range of potential  
175 nutrient management scenarios, the model predicts that different areas within LoW may respond differently to  
176 decreased phosphorus loadings. Reducing TP loading by 160 metric tons per year from the baseline condition  
177 improves the subbasin-specific trophic state (late-summer averages of TP to  $\sim 30 \mu\text{g/L}$  and total chlorophyll-a to  
178  $8-12 \mu\text{g/L}$ ; very close to Minnesota's regional standards and TMDL goals).

179  
180 Zastepa et al. (this issue a) provide two papers on cHABs. The first documents and characterizes previously  
181 unknown deep chlorophyll layers (DCL) in LoW. Five of 42 sites sampled contained at least one DCL in the  
182 metalimnion. Summer DCLs were not as deep as spring, due to reduced light penetration, and most were  
183 dominated by *Dolichospermum*. Drivers structuring the composition and activity of DCL are elusive, but DCLs are  
184 commonly observed in stratified water columns along a thermocline with sufficient light penetration and  
185 associated with an accessible, nutrient-rich hypoxic hypolimnion. It is suspected that microbial activity and  
186 allelopathy also play a role. Zastepa et al. (this issue b) reports on the prevalence and concentrations of more  
187 than 30 toxic / bioactive metabolites in cHABs in LoW. Between 2016 and 2019, most surface blooms were  
188 dominated by *Dolichospermum* and *Aphanizomenon*, with microcystins being common (80% of samples) but  
189 mostly below  $0.1 \mu\text{g/L}$  (max.  $\sim 33 \mu\text{g/L}$ , variant LR). Of the alkaloids, the neurotoxin anatoxin-a was common  
190 (60% of samples) but in low concentrations ( $<0.1 \mu\text{g/L}$ ). Anabaenopeptins (A,B,F) were prevalent ( $>96\%$ , max  
191  $>4,000 \mu\text{g/L}$ ) and exceeded microcystin concentration by  $>100$  times. Microcystin and anabaenopeptin genes  
192 were also detected in most samples (78% and 79%, respectively), while saxitoxin, cylindrospermopsin, and  
193 anatoxin genes occurred at lower frequencies with 59%, 36%, and 38% detection, respectively. Results will aid  
194 risk assessment from cHABs in LoW. Binding et al. (this issue) report on 20 years of satellite-derived cHAB  
195 indices in LoW, assessing status, trends and drivers. The largest blooms recorded reached an area in excess of

196 3000 km<sup>2</sup>, covering more than 80% of the lake surface area; the areas of greatest concern for most prolonged  
197 bloom occurrence are in the south-east and east basins. Significant decreases in bloom intensity and severity are  
198 reported, suggesting the lake may now be responding to historical nutrient reductions. The greatest rates of  
199 decrease in bloom intensity are observed within the main water flow paths, with little change in the more  
200 isolated embayments, suggesting flushing plays a key role in regulating regional bloom severity. Bloom  
201 phenology is shown to vary inter-annually, with severe blooms peaking towards the end of August and milder  
202 blooms peaking well into October. Results highlight the need for greater understanding of seasonal and regional  
203 variability of bloom drivers to inform on the lake's anticipated recovery under both nutrient management and  
204 climate change scenarios.

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## 206 **A roadmap for future transboundary water quality management in LoW.**

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### 208 ***Challenges to overcome***

209 LoW presents several scientific and governance challenges for policy makers, as restoration plans and  
210 phosphorus reduction goals are developed and implemented in the near future. Managing expectations and  
211 communicating these difficulties are critical steps. We also recognize that the established water governance  
212 structures in the LoW basin do not acknowledge or incorporate Indigenous rights, knowledge, or worldviews;  
213 considerable work is needed to create and advance equitable space to respect Indigenous knowledge, cultural  
214 protocols and governance (Clark et al., 2022). Some of these challenges are briefly summarized below.

- 215 1. LoW is a multi-basin lake with a nutrient gradient generally decreasing south to north (Clark et al.,  
216 2022), so one lake-wide TP objective or standard is not prudent. Currently, TP water quality objectives in  
217 LoW differ between Ontario, Manitoba, and Minnesota (Anderson et al., 2017). Preliminary discussions  
218 by resource managers suggest separate TP objectives for the northern and southern basins of LoW. This  
219 is also recommended by the ECCC integrated modelling framework, demonstrating that the complex  
220 topography and geometry of LoW, and nutrient deliveries in the basin, should be considered in modeling  
221 efforts to predict ecological responses to water management scenarios (Fong et al., this issue; Valipour  
222 et al., this issue; Rao et al., this issue).
- 223 2. LoW presents several governance challenges. There are 25+ agencies with land or water authorities in  
224 the LoW basin, ranging from local municipalities to Federal and Binational agencies (i.e. IJC); for  
225 example, Canada does not have a companion process to the US federal impaired waters / TMDL process.  
226 Also, importantly, the LoW basin includes over 20 First Nations within Canada, the Métis Nation of  
227 Ontario (Region 1), three Federally recognized Tribes within the State of Minnesota, and the 1854 Treaty  
228 Authority - an intra-tribal natural resource management organization that protects off-reservation rights  
229 in lands ceded to the U.S. Government. Thus, watershed planning processes must acknowledge and  
230 include Indigenous knowledge systems and cultural protocols to ensure respectful and meaningful  
231 decision-making and governance within the Basin (Clark et al., 2022). One event that has helped bridge

232 governance challenges has been the long-running Rainy-Lake of the Woods Watershed Forum. The  
233 Forum has met annually since 2004 to connect multi-jurisdictional working groups, stakeholders,  
234 resource professionals, and researchers from throughout the basin in a community building effort  
235 centered on prioritizing needs and guiding the future of LoW and its watershed.

- 236 3. LoW and its basin have been subjected to decades of environmental degradation. Accordingly,  
237 restoration will be long term (decadal scale), as the lake recovers from historical point-source impacts  
238 and responds to future management actions. Conventional lake restoration methods, such as P  
239 inactivation, are not logistically or economically feasible in the expansive, wind-swept southern basins of  
240 LoW. Major components of external P loads to LoW are not subject to conventional best management  
241 practices (e.g., atmospheric deposition; MPCA, 2021).
- 242 4. Like other large boreal lakes across the globe (Jenny et al., 2020; O'Reilly et al., 2015), LoW is especially  
243 sensitive to climate change (Paterson et al., 2017; Ruhland et al., 2010 and 2018) and restoration  
244 progress as measured by nutrient reductions will likely be confounded by climate change effects (Smith  
245 et al., 2019).
- 246 5. Aquatic stressors of the LoW basin are many, cumulative, and often linked with land use changes and  
247 economic drivers. The region's economy is changing; historically the economy was driven by timber  
248 harvesting and the forest products industry (Benidickson et al., 2019). However, this sector is declining,  
249 while mining and agriculture are growing in importance (Moazzami, 2019).
- 250 6. We must learn from water quality management successes and challenges from other North American  
251 transboundary lakes with eutrophication concerns - notably Lake Champlain (Osherencko, 2014; Lake  
252 Champlain Basin Program, 2021), Lake Erie (GLWQA NAS, 2019), and Lake Winnipeg (ECCC and  
253 Manitoba Agriculture and Resource Development, 2020). All three lakes, or their watersheds, are under  
254 IJC authorities; some are further along in the management process than LoW. A recent review on how  
255 HABs are being addressed by governments and non-government organizations in twelve case studies  
256 world-wide (Foulon et al., 2020) showed the importance of mobilizing all stakeholders around key  
257 issues, building trust around nutrient reduction strategies, and the need for clear governance, and  
258 strong leadership for success. Water quality management reviews have been published for these  
259 transboundary waters (Osherencko, 2014; Smith et al., 2019; Foulon et al., 2020; Macrae et al., 2021).

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#### 263 **Research gaps and monitoring needs for the LoW basin:**

- 264 1. Numerous monitoring projects and programs exist in the LoW region (e.g., ECCC's Science Plan), but  
265 there is a need for a coordinated, integrated, long-term monitoring program at the basin-scale. Such a  
266 program could be used to monitor water quality objectives and alert levels of aquatic ecosystems health  
267 and provide early detection of emerging stressors.

- 268 2. The development of a core set of monitoring locations across the basin, and monitoring a similar set of  
269 parameters using consistent methods, are needed to evaluate the effectiveness of management  
270 recommendations as they are implemented. This has been a priority since the IJC's Plan of Study for the  
271 LoW basin (IJC, 2015).
- 272 3. As mentioned above, there is a need to meaningfully integrate First Nation and Tribal knowledge into  
273 water quality management and decision-making, including incorporating Tribal perspectives into  
274 traditional western science approaches.
- 275 4. The role of temporary anoxia in driving internal P release from lake and tributary sediment needs to be  
276 studied further, within the context of climate change and variability in annual climate patterns.  
277 Temporary anoxia can be an important source of dissolved P to LoW, the Rainy River and its tributaries  
278 (Heathcote et al., 2020; Reid et al., this issue; Macgillivray et al., this issue).
- 279 5. More work is needed to understand the role of brownification and eutrophication of downstream  
280 waters in forested landscapes (Corman et al., 2018), particularly as new evidence suggests that dissolved  
281 organic carbon concentrations in regional lakes may now exceed pre-industrial levels (Meyer-Jacob et  
282 al., 2019).
- 283 6. There is a need to re-core the southern basin sediments to confirm the modeling hypothesis of  
284 incremental flushing of legacy P in surficial sediment (~ 1 % release annually in southern basins; Edlund  
285 et al., 2017a); cores for that study were collected in 2014, prior to the closing of a pulp and paper mill in  
286 Fort Frances, Ontario, a significant source of anthropogenic P to southern LoW.
- 287 7. Quantifying the depositional role of 4 Mile Bay in storing / releasing legacy P from Rainy River into LoW;  
288 including a potential lag in nutrient delivery from seasonal high flow and storm events.
- 289 8. A better understanding of atmospheric sources of dry depositional material / nutrients from agricultural  
290 regions south, west, and north of LoW is needed, building on the work of Eimers et al., this issue.
- 291 9. The importance of mitigating P at both high and low flow, particularly in drained systems (Smith et al.,  
292 2019) is also important for LoW and downstream in its receiving water Lake Winnipeg.
- 293 10. Impact of the recent zebra mussel infestation on lake ecology, including their likelihood of having  
294 significant trophic impacts within the moderate calcium waters of LoW and other large upstream lakes,  
295 such as Rainy Lake.
- 296 11. Improved understanding of the drivers of cHAB onset, toxin production, and how climate and remote  
297 sensing datasets (Binding et al., this issue) can best protect aquatic recreation and public health in LoW  
298 basin waters.
- 299 12. Ongoing reporting of satellite-derived algal bloom indices (Binding et al., this issue) as response  
300 indicators to track progress toward meeting proposed lake ecosystem objectives, while also tracking  
301 changes in DCLs, which is not captured with satellite-derived indices.
- 302 13. ECCC's existing water quality program (sampling 30 sites in LoW twice annually in June and September)  
303 provides valuable spatial coverage but lacks sufficient temporal resolution (including winter) to help

304 better understand mechanisms behind a range of observed physical and biogeochemical processes,  
305 drivers of cHAB onset and coincident cyanobacterial toxin production, and model validations. Biweekly  
306 sampling at several representative sites is desired.

307 14. Establishing a winter monitoring program for in-lake hydrodynamics and water quality when ice is  
308 developed (e.g., December through March) could further clarify the potential contributions of colder  
309 months to ice-free nutrient bioavailability and development of seasonal blooms.

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312 This special section of the *Journal of Great Lakes Research* is the first to address our current research and  
313 directives on how to restore and manage LoW and its watershed in a future certain to bring change. The papers  
314 herein address these research needs and key management issues that are required to manage this expansive  
315 multijurisdictional watershed.

316

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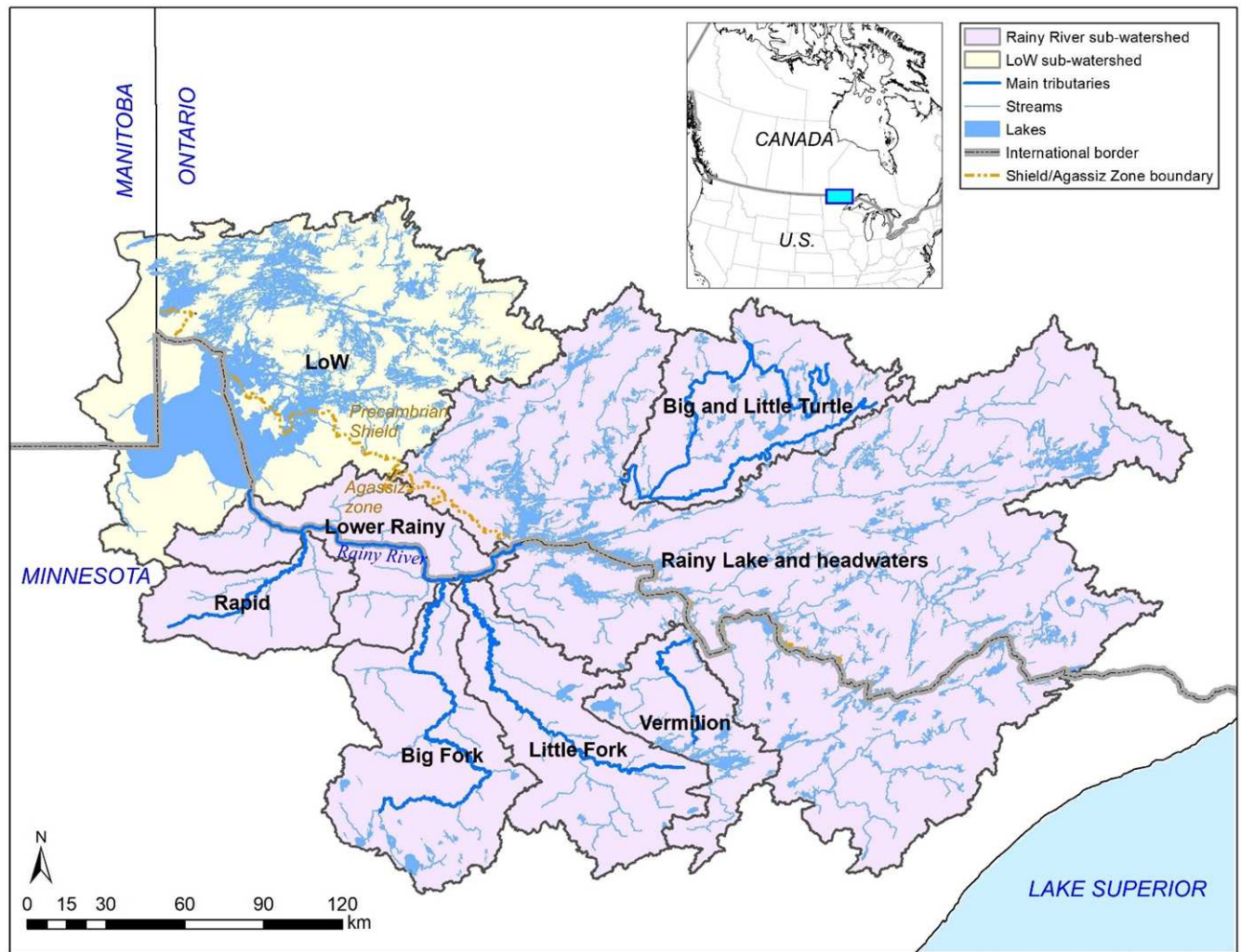
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536 Figure 1. The Lake of the Woods watershed, reproduced from Fong et al., this issue.

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