ENVIRONMENTAL STUDY ON SEDIMENT QUALITY IN LAC NOIR AND THE IMPACTS OF THE USE OF POWER-DRIVEN VESSELS

For

Association de protection de l’environnement du Lac Noir et de la Rivière Noire

By

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Executive summary

Lac Noir in the Lanaudière region is a vacation destination, where a balance must be struck between recreational uses, environmental protection and current regulations. The *Canada Shipping Act, 2001* regulates the use of pleasure craft in Canada, but is enforced in Quebec by the Sûreté du Québec under an agreement with the federal government. However, municipalities can adopt bylaws on the use of these vessels with authorization from the federal government.

Several studies have shown the impact of power-driven vessels on lake ecosystems. However, a comparative study has yet to be performed on a single lake with an exhaustive range of boats, to test their environmental impacts. This study focuses exclusively on recreational boating uses in Lac Noir and their effects on water and sediment quality. It has two objectives:

1- To characterize the quality of the bottom sediments in Lac Noir. The composition and grain size of the sediments in Lac Noir must be known in order to elucidate the mechanisms behind and risks of their resuspension. This initial characterization allows the areas in the lake with the greatest pollution risks to be identified.

2- To determine the impact of boating practices and motorized water sports on the resuspension of bottom sediments in Lac Noir.

According to the results on sediment quality, the bottom sediments in Lac Noir are non-cohesive and very fine, and thus easily mobilized. Moreover, they contain large amounts of phosphorus and certain heavy metals of unknown origin. The presence of phosphorus could lead to the development of cyanobacteria blooms, a public health risk that is increasingly present in Quebec lakes. The heavy metals could be associated with other health problems. Although Lac Noir is currently considered a mesotrophic lake by MDDELCC, its quality could deteriorate rapidly if motorized water sports and boating activities are not controlled.

Motorized boating impacts the water column at different depths depending on the activity. The activity with the most significant impact is undoubtedly wake surfing, which can disturb the water column to depths as great as 6 m. The velocities at this depth generated by wake surfing are capable of remobilizing the very fine, non-cohesive bottom sediments in Lac Noir.

Given the potential impact of motorized boating on aquatic ecosystems, boating activities should be limited or restricted and properly managed. However, in the interest of striking a balance between the needs of environmental preservation and recreational activities, the management strategies and

regulations adopted must be based on science and facts. The existing regulations (speed limits and distance from the shoreline) have not kept up with changes in vessel power and boating practices, including the adoption of new water sports. Regulations, and therefore legislation, need to evolve and be strengthened to keep pace with current realities. Based on this study, and taking into account previous studies, several types of recommendations can be proposed:

- During wind events, motorized water sports and boating activities should be limited or even prohibited to prevent the cumulative impact of disturbances.
- After a wind event, the lake should be allowed to rest for at least 24 hours to allow sediments to settle to the bottom and limit the release of phosphorus.
- All activities with wake boats should be prohibited except under the following conditions: a minimum depth of 7 m and a minimum width of 600 m.
- All activities with middle- or rear-engine water sports boats should be prohibited except under the following conditions: a minimum depth of 5 m.
- All activities with pontoon boats or personal watercraft should be prohibited except under the following conditions: a minimum depth of 2 m.
- Vessels operating in depths of less than 2 m must proceed at the slowest possible speed and accelerate slowly and gradually.

When these principles of sound environmental management are applied to Lac Noir, **no areas of the lake appear suitable for wake surfing or wake boarding**. Water sports boats with middle engines could operate in a limited area, and various boating activities such as the use of personal watercraft and pontoon boats could be permitted in a larger area. However, areas near the shoreline and in Baie des Bounadère are not suitable for any motorized water sports, although navigation at low speeds without sudden acceleration could be acceptable. These restrictions could also be extended to Rivière Noire, where slow speeds with no acceleration could be allowed. Quebec has a multitude of lakes with diverse characteristics, and wake boarding could be done on other lakes of a suitable width and depth.

1. Background and issues

Lake aging is a natural phenomenon that normally occurs over several hundreds to thousands of years. This phenomenon, known as eutrophication, is defined as the process in which a lake or other water body becomes gradually enriched with nutrients, transforming it from oligotrophic (low nutrient content) to eutrophic (high nutrient content). The accumulation of nutrients leads to increased biological production, which is accompanied by a transformation of the lake's characteristics. In particular, this results in larger amounts of sediments and organic matter on the lake bottom, a reduction in dissolved oxygen in the lake water and the replacement of the organisms in the lake by species better adapted to the new conditions. Eutrophication can be accelerated by human activities on the shore, in the watershed and in the lake itself. These activities can increase nutrient inputs to the lake and also remobilize nutrients already present in the lake, particularly in the sediment.

Premature lake aging due to human activities is one of the main problems affecting lakes in cottage country and in agricultural and urban environments, and Lac Noir in the Lanaudière region is no exception. It is a vacation destination, where a balance must be struck between motorized water sports and recreational boating activities, environmental protection and the existing regulations. According to observations by residents over the past 10 years, boating has increased on Lac Noir, and recreational activities have changed. New water sports have emerged, such as wake surfing and wake boarding (Figure 1).

Figure 1: Wake surfing

(Source: http://www.skimboard.com/edenv3/index.php?option=com_content&view=article&id=114&Itemid=810)

These activities require particularly powerful vessels (over 350 hp) called wake boats, whose environmental impacts in lakes are just beginning to be studied (Mercier-Blais and Prairie 2014; Raymond and Galvez 2015). However, a comparative study in a single lake using a wide range of vessel types to assess their environmental impact has yet to be carried out. Consequently, this study is limited to boating uses and water and sediment quality in Lac Noir.

"The main issue in most of our lakes is maintaining their natural trophic state. The pressure on these lakes varies from place to place, but is sometimes very strong with regard to occupation of their shorelines and watersheds. The main consequence of this pressure, and the one that is currently of the greatest concern to residents and decision-makers alike, is the increase in nutrient levels in water bodies, which often results in a change in their trophic status. These changes, which always involve increases, are most often difficult to reverse."[1] [translation]

The Association de protection de l'environnement du Lac Noir et de la Rivière Noire [Lac Noir and Rivière Noire environmental protection association] commissioned Dr. Sébastien RAYMOND (PhD) and Professor Rosa GALVEZ (PhD, Eng.) to carry out a study to characterize the bottom sediments in the lake and the impact of boating on the water column and the resuspension of bottom sediments. This study must allow the Association to propose regulations (bylaws) on boating uses based on the scientific results and in situ testing. The quality of the lake's bottom sediments will be assessed based on a sampling plan. At the same time, a comparative study will measure the environmental impact of motorized water sports and boating activities on the water column and the potential resuspension of bottom sediments.

2. Project objectives

The project has two complementary objectives. The first is to determine the state of the bottom sediments in Lac Noir. Information on the composition and grain size of these sediments is essential in order to define areas of phosphorus and heavy metal pollution and estimate the risks of resuspension,

1 Source: "Interprétations reliées à la problématique des apports en nutriments pour les lacs, Bassin versant de la rivière L'Assomption," Daniel Blais and Adeline Bazoge, November 2005, MDDELCC.

respectively. This initial characterization stage will enable us to determine the areas with the greatest pollution risk.

The second objective is to measure the depths impacted by the various types of power-driven vessels on the lake and to determine whether these vessels generate a sufficient disturbance to resuspend bottom sediments.

These results are intended to provide a technical and scientific basis for the Association to support regulations to preserve the quality of Lac Noir's waters.

3. Study site

Rivière Noire is located in the Rivière L'Assomption watershed (Figure 2). The entire Rivière Noire subbasin is situated in the southern Laurentians physiographic region, and originates in the northeastern part of the drainage basin, in the hills of the municipality of Saint-Zénon. Lac Noir is not the headwater lake, but is the largest body of water in an area of 414 km^2. Rivière Noire flows over a length of 63 km and has an average gradient of 5.2 m/km and an average flow rate of 1.2 m^3/s.

Lac Noir has an average depth of 4.5 m, and a maximum depth of 7 m. The bathymetric chart of Lac Noir is available in Figure 3. It has a surface area of 243 ha and an elevation of 202 m. Lac Noir is 3.2 km long (north to south) and 1.4 km wide on average. Its geographic coordinates are 46° 16′ 47″ north and 73° 32′ 36″ west.

The water renewal rate in the lake is 22 times a year, or approximately 1.8 times per month. Rivière Noire, which flows through the lake, provides a significant and steady source of water, playing a major role in the lake's surface water quality.

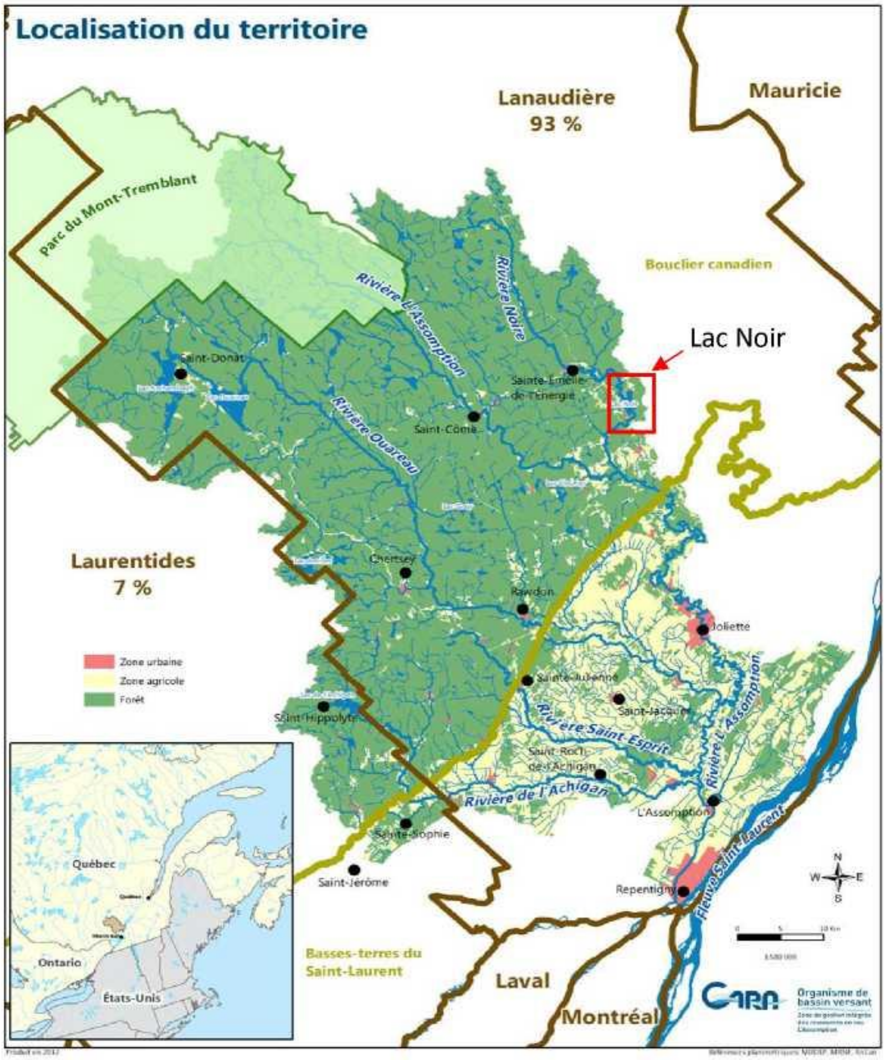


Figure 2: Location of Lac Noir in the Lanaudière region

EN	FR
Location of study area n	Localisation du territoire
Urban area	Zone urbaine
Agricultural area	Zone agricole
Forest	Forêt
Mont-Tremblant provincial park	Parc du Mont-Tremblant
Canadian Shield	Bouclier canadien
St. Lawrence Lowlands	Basses-terres du Saint-Laurent
Rivière Noire	Rivière Noire
Rivière L'Assomption	Rivière L'Assomption
Rivière Ouareau	Rivière Ouareau
Rivière de l'Achigan	Rivière de l'Achigan
Rivière Saint-Esprit	Rivière Saint-Esprit
St. Lawrence River	Fleuve Saint-Laurent
Lac Noir	Lac Noir
Watershed organization	Organisme de bassin versant

L’Assomption integrated water resource management area	Zone de gestion intégrée des ressources en eau de l’Assomption
Horizontal reference: MDDEP, MRNF, NRCan	Références planimétriques MODEP’ MRNF, RnCan

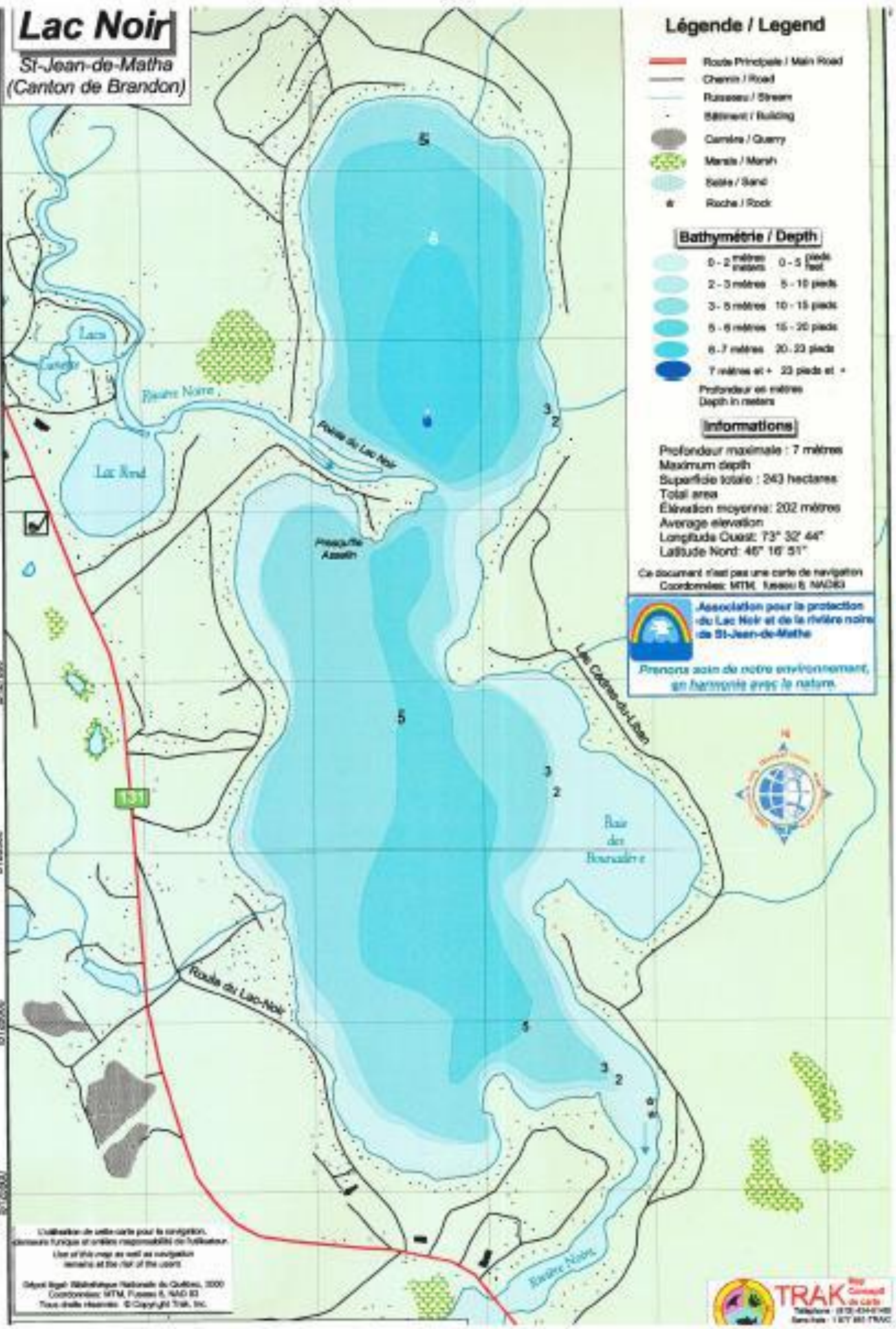


Figure 3: Bathymetric chart of Lac Noir

4. Methodology

The methods used in the study are based on a proposal submitted to the Association de protection de l'environnement du Lac Noir et de la Rivière Noire in July 2016 for an environmental study on sediment quality in Lac Noir and the impact of power-driven vessels.

The project was divided into four phases covering all of the objectives identified above, namely the characterization of sediment quality and the impact of motorized boating on the resuspension of bottom sediments. These four phases involved two distinct fieldwork campaigns, a laboratory analysis phase and a writing and communication phase.

4.1. Characterization of sediment quality

Sediment characterization was based on core samples taken from the lake bottom, which were then sectioned and analyzed at Université Laval's environmental laboratory. The sampling plan and analyses are described below.

4.1.1. Sampling plan

A sampling campaign to collect bottom sediment cores from Lac Noir was carried out in summer, on August 24, 2016. Five samples were taken at various strategic points in the lake, enabling a complete assessment of its bottom sediments (Figure 4).

Zone d'echantillonage	Sampling sites

Figure 4: Location and numbering of sediment cores

The sampling followed the recommendations in Environment Canada's (1999) protocol for sampling sediments to determine their nutrient and metal content and physical characteristics. The strategy aimed to sample all areas in the lake, the coordinates of which are presented in Table 1, in order to define contrasting pollution sectors.

Table 1: Coordinates of Lac Noir bottom sediment samples

Sample number	Coordinates (XY)		Core length (in metres)
	Easting (X)	Northing (Y)	
1	612143.75° E	5127338.44° N	0.60
2	612109.48° E	5126860.05° N	0.40
3	612303.52° E	5125987.25° N	0.50
4	612298.30° E	5125470.83° N	0.50

5	**611841.38° E**	**5126244.35° N**	**0.50**

4.1.2. Analysis of parameters

<u>Analysis protocol:</u>

The sediment cores were analyzed in the environmental laboratory of Université Laval's Department of Civil and Water Engineering, in accordance with the standards for the parameters to be analyzed.

The cores were sectioned manually as shown in Figure 5: 0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, etc. The surface layer was sectioned every 5 cm, and from a depth of 10 cm onwards, the cores were cut every 10 cm (see Appendix 1).

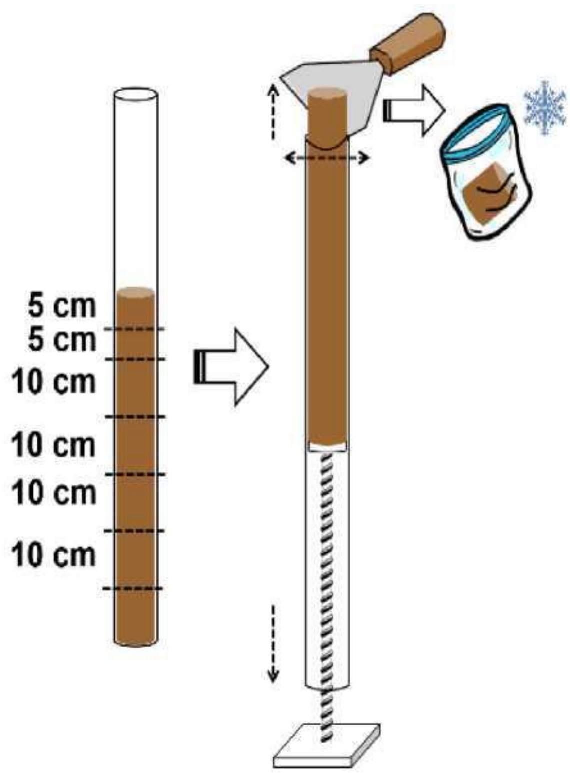


Figure 5: Illustration of sectioning of samples and associated depths

Each analysis was carried out in triplicate to ensure the validity of the results. The parameters analyzed and the methods used are presented in Table 2:

Table 2: Parameters analyzed and associated methodology

Parameters	Methodology
Water content (WC)	Weight loss at 105 °C
Organic matter (OM) - Total organic C (TOC)	Loss on ignition at 550 °C (LOI)
Pore water extraction	Centrifuge dewatering
Pore water pH	pH meter (S 940, Multi 3430 SET G, WTW)
Electrical conductivity (EC) of pore water	Conductivity meter (TC 925, Multi 3430 SET G, WTW)
Soluble phosphorus in pore water	UV spectrophotometry, ascorbic acid method (Hach©)
Available phosphorus	Olsen method: Extraction with $NaHCO_3$ and measurement with UV spectrophotometry, ascorbic acid method (Hach©)
Grain size	H_2O_2 digestion in a water bath and measurement with a laser particle size analyzer (Horiba©)
Pseudo-total trace metal elements (TMEs)	Aqua regia (HNO_3/HCl) digestion and measurement with a flame atomic absorption spectrometer (AA240FS, Varian Inc.)

The values obtained for the parameters were then compared with the quality criteria defined by Environment Canada and Quebec's Ministère du Développement durable, de l'Environnement, et de la lutte contre les changements climatiques (Environment Canada and MDDELCC 2007), when available.

These analyses were completed in full, enabling available phosphorus levels (the main factor in eutrophication), concentrations of heavy metals and the physicochemical characteristics of the sediments in Lac Noir to be characterized.

4.2. Assessment of impact of power-driven vessels

In order to assess the impacts of boating activities on the water column, an experimental design was employed to evaluate several types of vessels, using an Acoustic Doppler Current Profiler (ADCP).

4.2.1. ADCP basics

An ADCP is an instrument that has the following characteristics:

- Acoustic – Use of sound waves
- Doppler – Doppler effect (change in a wave's observed frequency between the value measured at the source and at the observer) applied to velocity measurements
- Current – Measurement of water velocity
- Profiler – Measurement of a velocity profile, not a point velocity

Data are recorded, then extracted and processed in the ADCP to determine the direction and intensity of the current.

The ADCP calculates components of water velocity at various depths of the water column in all three directions. The device makes it possible to calculate velocity and determine the direction of the current in all parts of the water column. Velocities are determined in each cell (the water column is divided into vertical segments), whose size and number can be adjusted; a vertical segment made up of several cells is called an ensemble. The Doppler effect makes it possible to transmit sounds at fixed frequencies and receive echoes returned by scatterers in the water. Scatterers are small, microscopic particles of sediment or plankton that are naturally present in the water. They travel at the same speed as the water and reflect sound back to the ADCP. The ADCP model chosen for the tests has four transducers that emit sound pulses at frequencies of about 1.2 MHz. The pulses are reflected and somewhat deformed by the particles (scatterers) suspended in the water, depending on their speed. The distance between the particle (scatterer) and the ADCP is calculated based on the interval between the emission and return of the pulse (Lane et al. 1999; RD Instruments 1989). Although the sound velocity depends on the density of the medium along the acoustic path, the horizontal component of the number of waves is maintained and this makes it possible to determine horizontal velocities based on the known sound velocity at the transducer alone. Thanks to the Doppler effect, the system calculates the water velocity in three dimensions (one vertical and two horizontal dimensions) perpendicular to each beam (three or four beams) using trigonometry.

4.2.2. Vessel inventory

As the study was specifically intended for Lac Noir, it was suggested that a range of vessels representative of the ones used on the lake be included. The number and types of vessels were proposed by the Association, and are listed below and shown in Appendix 2:

- ✓ MOOMBA wake boat for wake boarding and wake surfing: ± 400 hp rear engine
- ✓ BOMBARDIER jet-drive personal watercraft: ± high-performance 90 hp model
- ✓ ARCTIC CAT jet-drive personal watercraft: conventional 70 hp model
- ✓ MASTERCRAFT water sports boat: 305 hp middle engine
- ✓ GLASTRON water sports boat: 190 hp rear engine
- ✓ Pontoon boat: 18 ft., 25 hp
- ✓ Pontoon boat: 22 ft., 90 hp

4.2.3. Experimental design

The experimental design used in this study made it possible to determine which type of vessel commonly used on the lake was likely to cause the resuspension of sediments on the lake bottom. The proposed solution was therefore to use the ADCP to measure the intensity of the disturbance in the water column after the passage of each vessel.

These data made it possible to determine the critical threshold (depth) for sediment resuspension based on vessel type.

The work included one day on the lake on September 15, 2016. The installation of an ACDP was necessary. Each vessel passed over the ADCP three times, once in normal operation, once while accelerating and once while making a turn (if part of customary navigation). All the passes are summarized in Table 3.

Table 3: Operating conditions for the power-driven vessels assessed in this study

Vessel type	**Horsepower**	**Speed**	**Accelerating**	**Turning**	**Details**
Ponton boat (18 ft.)	25 hp	**15 km/h (± 5 km/h)**	No	No	**5 people on board**
Pontoon boat (22 ft.)	90 hp	**15 to 20 km/h (± 5 km/h)**	No	No	**2 people on board**
Water sports boat (middle engine)	305 hp	**49 km/h (± 5 km/h)**	Yes	Yes	**2 people on board**
Water sports boat (rear engine)	190 hp	**42 km/h (± 5 km/h)**	Yes	Yes	**1 person on board**
Personal watercraft (high performance)	90 hp	**42 km/h (± 5 km/h)**	Yes	Yes	**1 person on board**
Personal watercraft (conventional)	70 hp	**40 km/h (± 5 km/h)**	Yes	Yes	**1 person on board**
Wake boat (wake surfing)	400 hp	**24 km/h (± 5 km/h)**	Yes	No	**5 people on board, plate up, stern ballast full**
Wake boat (wake boarding)	400 hp	**24 km/h (± 5 km/h)**	Yes	No	**5 people on board**

5. Results

The results of the various fieldwork campaigns on the lake are presented below, focusing first on the environmental assessment of sediment quality in Lac Noir and then on the impact of vessels on the water column.

5.1. Quality of bottom sediments

The physicochemical characteristics of the bottom sediments, including the concentrations of heavy metals and bioavailable phosphorus as well as grain size, are presented in this section in order to define potential areas of pollution.

5.1.1. Physicochemical characteristics

Physicochemical parameters and heavy metals were mainly measured in the first 10 cm of each core and are presented in Table 4. The study focused mainly on this sediment layer, as it could potentially be mobilized by disturbances caused by boating. These shallow sediments are less cohesive than the deeper, more compacted sediments in the lake bottom.

Water content (in %) is defined as the volumetric ratio of water to sediment. It is determined using the ratio of the wet mass to the dry mass in a given sample and corresponds to pore water content. Water content is a parameter directly related to grain size and is determined for applications such as the reclamation of dredged sediments. The water saturation measured in the surface sediments of the cores is a common phenomenon linked to the relatively uncompacted sediments in the first few centimetres, which makes them more easily mobilized during disturbances. A much lower water content was observed in core no. 2, collected in a shallower, narrower area. Flow velocities are higher in that area, suggesting that bottom sediments are subjected to greater erosion, resulting in sediments with a lower water content and greater cohesion.

Table 4: **Physicochemical characteristics of the first 10 cm of bottom sediments**

		WC	**Organic fraction**		**Pore water**		
Core	**Depth in core (cm)**	**% WC**	**OM (%)**	**TOC (%)**	**pH**	**EC (µS/cm)**	**Sol. P (µg/L)**
1	5	555.3	16.2	9.4	4.6	108.1	17.2
1	10	432.3	14.4	8.3	5.8	50.0	35.3
2	5	67.5	3.4	1.9	6.1	95.1	7.2
2	10	56.8	3.0	1.8	5.8	-	73.6
3	5	399.7	13.5	7.9	5.3	149.1	3.1
3	10	372.2	13.9	8.1	5.6	63.7	20.1
4	5	308.8	13.7	8.0	5.3	71.0	37.1
4	10	371.1	13.8	8.0	5.4	44.2	60.9
5	5	397.1	13.8	8.0	5.6	54.3	13.8
5	10	394.5	13.5	7.8	5.6	47.1	35.4

Organic matter (in %) is made up of the cells of micro-organisms, animal and plant matter in various stages of decomposition, stable humus, and compounds such as charcoal and graphite. Organic matter is therefore an indicator of the biological activity in sediments and their nutrient content. Organic fraction percentages were similar in core nos. 3, 4 and 5 and across all depths, with values of 13.5–13.9% for organic matter (OM) and 7.8–8.1% for total organic carbon (TOC). Core no. 1 had significantly higher percentages (14.4% to 16.2% for OM and 8.3–9.4% for TOC). These variations can be explained by the different flow velocities and depths, which modify the sedimentation process. Point 1 is located in the deepest portion of the lake, upstream of where Rivière Noire crosses the lake, while Point 2 corresponds to a narrowing just downstream of Rivière Noire, with shallower water and thus higher flow velocities and little sedimentation of OM and TOC.

In terms of the pH of the pore water in the sediments, little variation was found between cores, regardless of depth. However, in the first 5 cm of core nos. 1 and 2, the pH values were significantly different, at 4.6 and 6.3, respectively. These pH variations are correlated with organic matter content.

Electrical conductivity (in µS/cm) measures the ability of water to carry an electric current through the charged ionic species it contains. As such, this measurement is directly proportional to the concentration of ions in the water. Electrical conductivity ranged from 44.2 to 149.1 µS/cm. While most values were in the 44.2–71 µS/cm range, three values raised questions, namely those for the first 5 cm in core nos. 1, 2 and 3, which were two or three times those measured in the other cores. This suggests the presence of trace metal elements or major ions in significant concentrations. One factor contributing to the presence of these elements in the water may be the application of de-icing salts.

Soluble phosphorus concentrations in the pore water ranged from 3.1 to 73.6 µg/L. Concentrations were generally higher in the 5–10 cm layers. No quality criteria are available for soluble phosphorus concentrations in lake sediment pore water. The presence of soluble phosphorus in pore water is linked to pH, biological activity and the release of the ion from the solid phase. This dissolved form in pore water represents only a tiny fraction of the total phosphorus contained in sediments, at around 1% (Sondergaard et al. 2003).

Metals were measured to identify (i) potential sources of pollution external to the lake and (ii) immediate availability, which is closely related to toxicity.

No defined quality criteria are available for iron (Fe), manganese (Mn) and sodium (Na) in lake sediments. Other criteria exist, based on the toxicity thresholds defined in Table 5 (Environment Canada and MDDELCC 2007).

Table 5: Quality criteria for freshwater sediments

	Concentrations (mg/kg)				
Substance	REL	TEL	OEL	PEL	FEL
Cadmium	0.33	0.6	1.7	3.5	12
Chromium	25	37	57	90	120
Copper	22	36	63	200	700
Nickel	N/A	N/A	47	N/A	N/A
Lead	25	35	52	91	150
Zinc	80	120	170	310	770

REL = rare effect level; TEL = threshold effect level; OEL = occasional effect level; PEL = probable effect level; FEL = frequent effect level

For the prevention of sediment contamination due to a new input of contaminants into a water body (e.g., industrial or urban discharges), the rare effect level (REL) and threshold effect level (TEL) are the threshold values used to define the management framework. When the concentration of all substances analyzed is less than or equal to the REL, no action is planned, as the sediments are deemed to have no effect on the environment. When the concentration of one or more substances exceeds the REL but is less than or equal to the TEL (class 2), the probability of the sediment having an impact on the environment is considered low. However, monitoring measures may be planned to track changes in the situation. If concentrations increase, further investigations should be considered to identify the source of contamination and assess the environmental impact. When the concentration of one or more substances exceeds the TEL (class 3), the probability of observing adverse effects on benthic organisms increases with the concentration measured. If the measured concentration also exceeds background or ambient levels, the sources of contamination must be investigated, and if necessary, steps must be taken to contact those responsible in order to establish the measures necessary to limit contamination. To prevent further inputs of contaminants, additional restrictions may be imposed on any new facility whose discharges are likely to lead to an increase in concentrations above the TEL or above background levels in accumulation areas downstream, and sometimes even upstream, of the discharges.

Table 6: Trace metal element concentrations in sediments in Lac Noir

			Trace metal elements / Major cations								
Core	Depth in core (cm)	Cd	Cr	Cu	Ni	Pb	Zn	Fe (mg/kg dry)	Mn	Na	**Na (mg/kg)**
	1	5	1.8	12.0	20.7	16.7	19.9	208.1	51,480.3	394.7	502.5
	1	10	2.0	11.3	13.9	19.3	30.9	210.8	44,817.6	144.9	614.5
	2	5	0.8	2.5	1.7	2.6	<LQ	40.8	10,725.7	70.3	219.5
	2	10	0.8	2.7	1.1	2.7	<LQ	39.9	10,256.0	57.8	249.5
	3	5	2.0	10.3	11.6	16.9	32.9	245.5	57,715.7	1,070.5	541.5
	3	10	2.1	10.5	11.2	17.5	30.9	247.4	64,524.1	1,301.6	563.8
	4	5	2.0	9.7	10.0	15.2	26.9	218.2	49,220.0	1,081.4	535.7
	4	10	2.0	10.0	9.0	15.3	19.9	191.2	45,618.3	958.2	625.3
	5	5	1.9	10.4	10.3	17.0	24.9	226.9	60,357.8	1,269.6	556.0
	5	10	2.0	10.4	10.4	18.1	29.8	221.0	52,884.3	935.1	570.6

< LQ = below the limit of quantification

All the results for heavy metals measured in Lac Noir's bottom sediments are presented in Table 6. For cadmium (Cd), the measured values are between the OEL and the PEL for all cores except core no. 2 (concentration between the TEL and the OEL). For chromium (Cr), all concentrations are below the REL; the same is true for copper (Cu). Nickel (Ni) has no defined criteria like those for the other metals. However, an OEL value of 47 mg/kg is considered a threshold value; in this study, all Ni concentrations were below this value. For lead (Pb), with the exception of core no. 2, all values were between 19.9 and 32.9 mg/kg, i.e., between the REL and the TEL. For zinc (Zn), concentrations ranged from 191.2 to 247.4 mg/kg, with the exception of core no 2, for which concentrations were below the REL. For core nos. 1, 3, 4 and 5, concentrations were therefore between the OEL and the PEL.

Table 7: Heavy metal and major cation concentrations in three Quebec lakes (adapted from Environment Canada and MDDELCC 2007)

	Concentrations (mg/kg)		
Substance	**Lake Saint-François**	**Lake Saint-Louis**	**Lake Saint-Pierre**
Cadmium	0.8	1	0.4
Chromium	52	93	66
Copper	27	41	24
Nickel	28	20	26
Lead	25	38	19
Zinc	120	220	100
Iron	26,000	47,000	34,000
Manganese	560	1,100	720
Sodium	18,000	17,000	24,000

As there are no defined criteria for iron, manganese and sodium, the concentrations measured were compared to those established for Lake Saint-François, Lake Saint-Louis and Lake Saint-Pierre, three fluvial lakes in the St. Lawrence River (Environment Canada and MDDELCC 2007). Table 7 shows that iron and manganese concentrations were much higher in Lac Noir than in the fluvial lakes. In addition, manganese concentrations in the southern part of the lake (core nos. 3, 4 and 5) were two to three times higher than in the northern part (core no. 1), meaning that the distribution of this pollutant is variable. Conversely, concentrations of sodium were lower in Lac Noir than in the freshwater fluvial lakes of the St. Lawrence.

5.1.2. Bioavailable phosphorus

All cores were analyzed for bioavailable phosphorus, which is the form of phosphorus available to living organisms and thus the one involved in eutrophication processes.

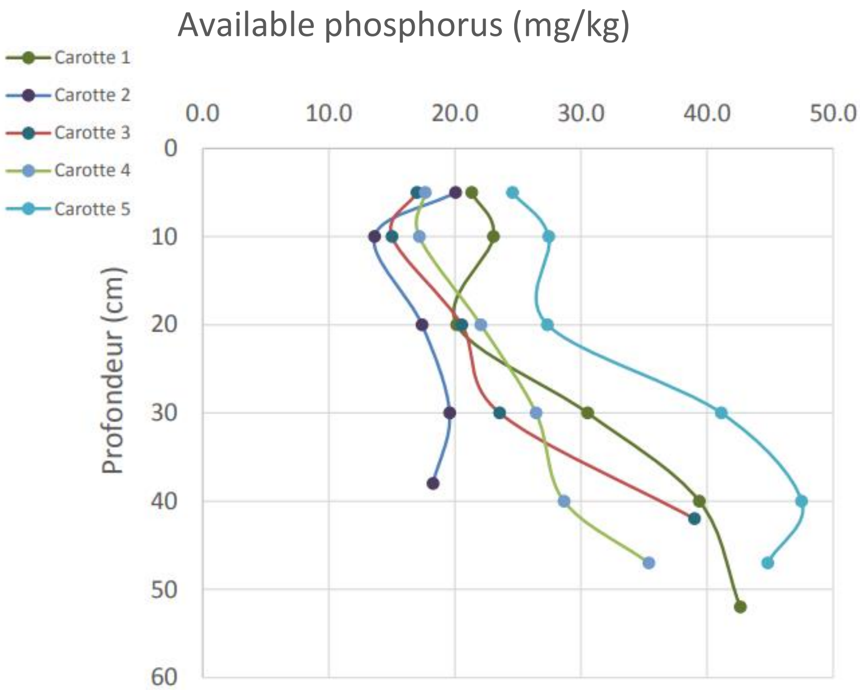


Figure 6: Bioavailable phosphorus concentrations as a function of depth

EN	FR
Core	Carotte
Depth (cm)	Profondeur (cm)

According to Figure 6, core no. 2 differed from the others, showing very slight variations in concentrations with depth, ranging from 13 to 20 mg/kg at depths of 5 to 40 cm. For the other cores, concentrations ranged from 17 to 25 mg/kg at a depth of 5 cm, gradually increasing to a maximum of 48 mg/kg, with the greatest increase at depths greater than 20 cm. This suggests that phosphorus inputs in the lake have gradually decreased over the last few decades, due to measures such as septic system retrofits, the use of phosphate-free detergents and shoreline revegetation. However, past actions have contributed to the creation of a phosphorus reservoir in the lake, which could potentially exacerbate eutrophication.

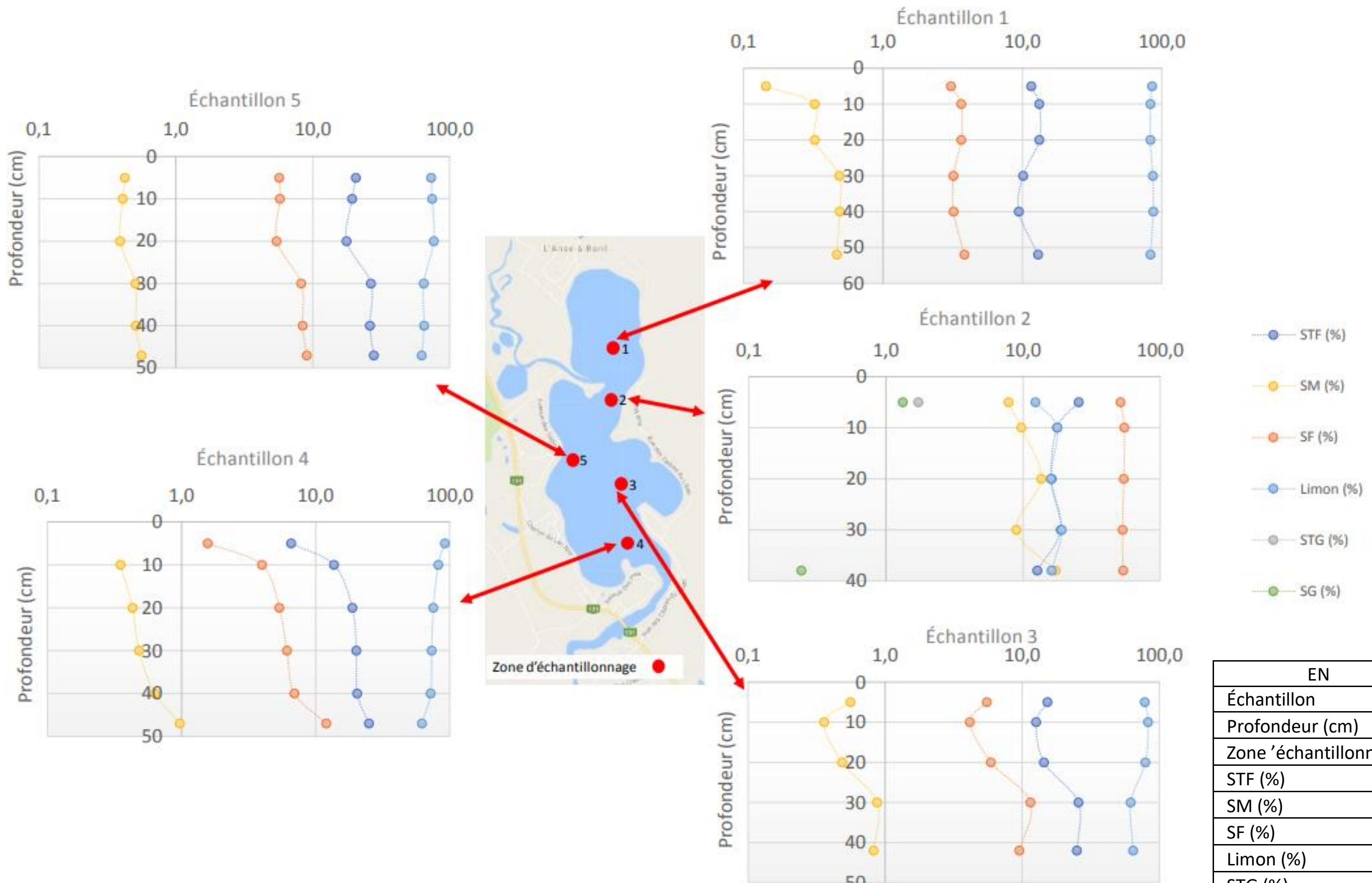
5.1.3. Grain size

A grain size analysis was carried out to determine, among other things, whether the bottom sediments in the lake could be mobilized, and if so, at what velocity. A number of parameters can be used to characterize sediments, including grain size, water content and organic matter (Schneider 2001). Sediment grain size was measured in order to understand the source of sediment inputs to the lake. This parameter tells us the size distribution of mineral particles in the sediment, i.e., the proportions of sand, silt and clay, and is essential for assessing the immediate and potential availability of nutrients and pollutants. The grain size of the sediments in the cores was defined based on the criteria described in Table 8.

Table 8: Definition of grain size based on diameter

	Particle diameter	
	In mm	In µm
VCS: Very coarse sand	1–2	1,000–2,000
CS: Coarse sand	0.5–1	500–1,000
MS: Medium sand	0.25–0.5	250–500
FS: Fine sand	0.1–0.25	100–250
VFS: Very fine sand	0.05–0.1	50–100
Silt	0.002–0.05	2–50
Clay	< 0.002	< 2

The sediments in the first 50 cm consisted mainly of silt (almost 80%) and very fine sand (around 12%) (Figure 7). In combination with the high water content, this suggests very fine, non-cohesive sediments that could be remobilized even by low flow velocities. A 50-µm clay particle would require a flow velocity of 12 cm/s, and a 2-µm particle, a velocity of 2.5 cm/s (Beachler 2002). This information will be critical in determining the appropriate management of motorized water sports and boating activities.



EN	FR
Échantillon	Sample
Profondeur (cm)	Depth (cm)
Zone 'échantillonnage	Sampling area
STF (%)	VFS (%)
SM (%)	MS (%)
SF (%)	FS (%)
Limon (%)	Silt (%)
STG (%)	VCS (%)
SG (%)	CS (%)

Figure 7: Grain size of bottom sediments in Lac Noir

5.2. Impacts of boating

The impacts of boating on the water column in Lac Noir were measured using ADCPs. The set of figures presented below shows the intensity of disturbance of the water column, expressed as the number of pings (the unit of measurement used). One can indeed surmise that, the more water is disturbed, the greater the quantity of scatterers present (agitation of suspended solids, oxygen supply in the environment), and therefore the greater the number of pings sent back to the ADCP. The yellow to red areas in the figures therefore experience the most disturbance.

Figure 8 shows the results of all the tests carried out in Lac Noir for all the vessels tested. A more detailed analysis of the impact of each vessel type will be presented below. However, in Figure 8, you can already see that all of the vessel types had some impact on the water column, with clear differences based on the boating practice or water sport. For all vessels, the maximum disturbance (red area) occurred at a depth of around 1 m, but significant disturbances (yellow to orange areas) took place at depths as great as 6 m.

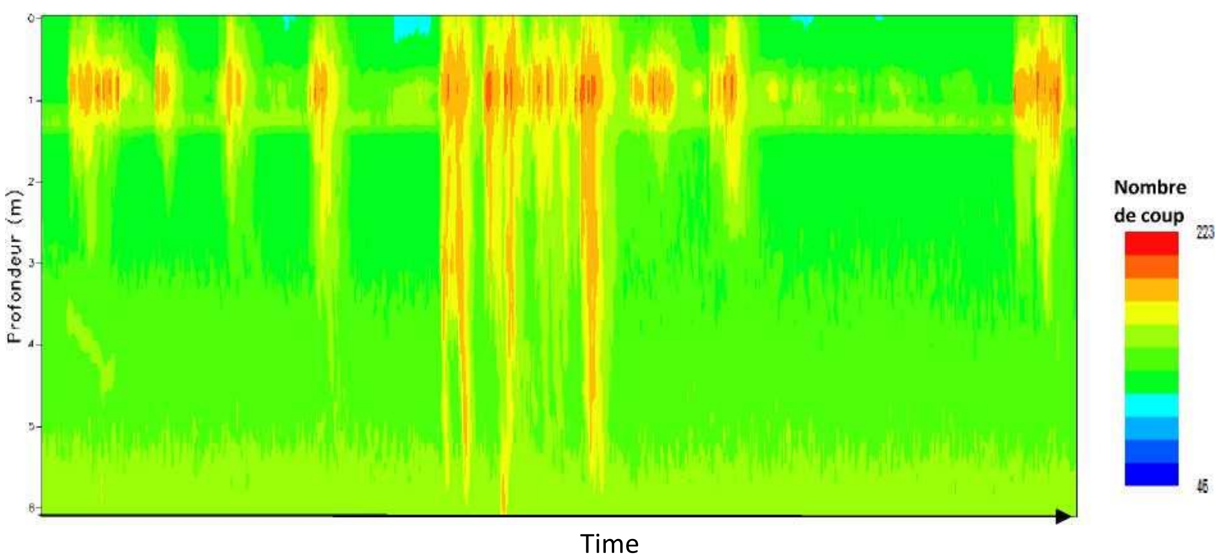


Figure 8: Impacts of the vessel fleet as a whole on the Lac Noir water column

EN	FR
Profondeur (m)	Depth (m)
Nombre de coup	Number of pings

5.2.1. Impacts of the Lac Noir vessel fleet

Figures 9 and 10 show the impacts by vessel type, illustrating the resulting disturbance at a typical operating speed in a straight line, during acceleration and during turns.

Figure 9 shows that the impacts from a pontoon boat (25 hp), a conventional 70 hp personal watercraft and a rear-engine water sports boat were limited to depths of less than 2.0 m or even 1.5 m (personal watercraft and water sports boats under typical operating speeds and while turning). Rear-engine water sports boats, when accelerating, can impact the water column to a depth of 3 m.

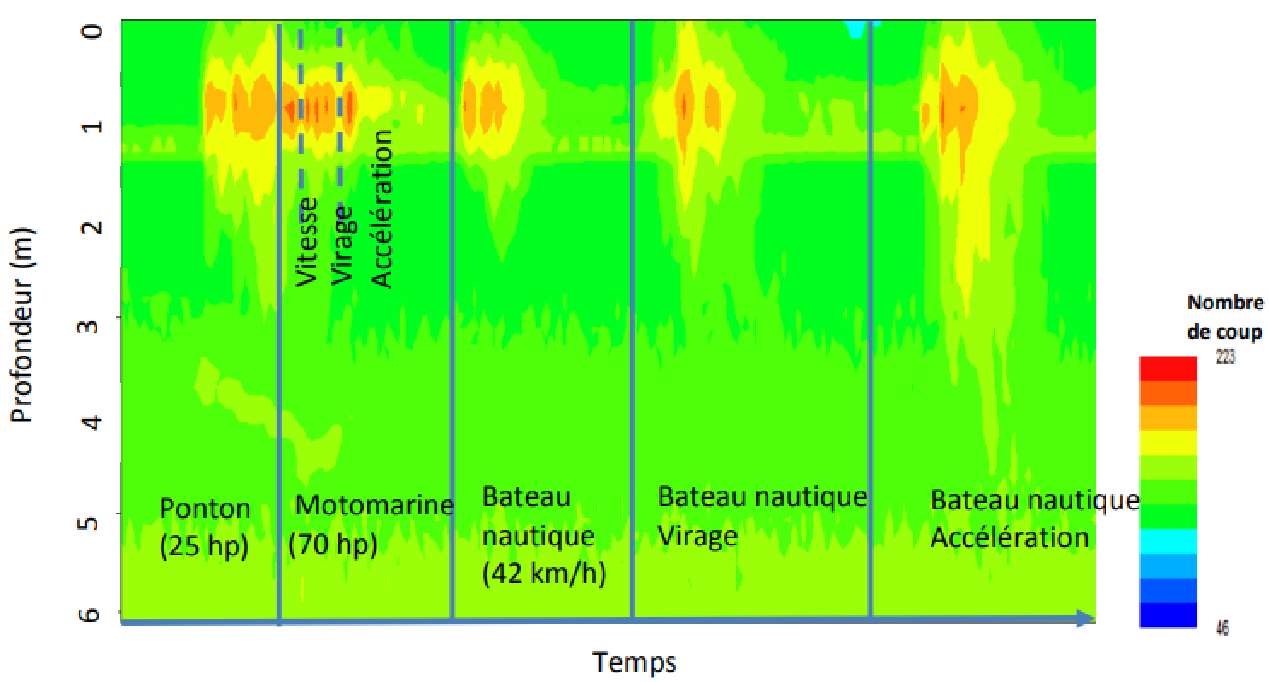


Figure 9: Impacts of different types of power-driven vessels by operating mode

FR	EN
Profondeur (m)	Depth (m)
Temps	Time
Vitesse	Speed
Virage	Turning
Accélération	Accelerating
Ponton (25hp)	Pontoon boat (25 hp)
Motomarine (70hp)	Personal watercraft (70 hp)
Bateau nautique (42 km/h)	Water sports boat I (42 km/h)
Bateau nautique Virage	Water sports boat Turning
Bateau nautique Accélération	Water sports boat Accelerating
Nombre de coup	Number of pings

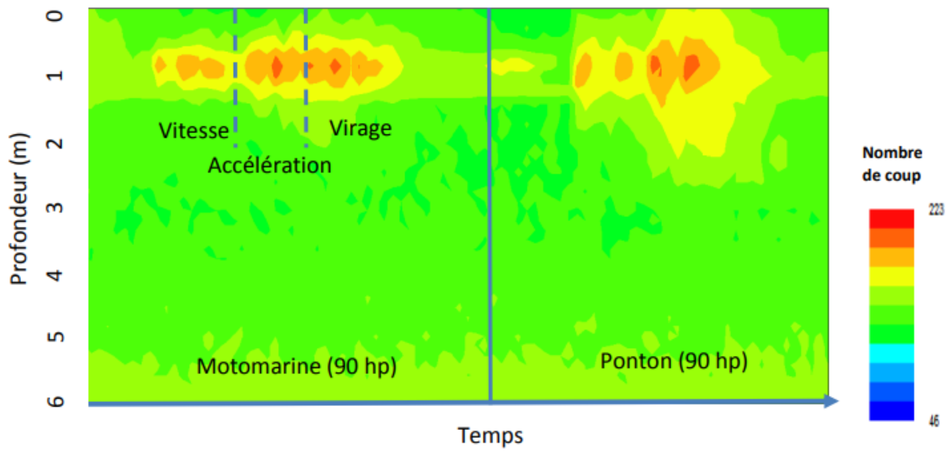


Figure 10: Impact of personal watercraft and pontoon boats by operating mode

FR	EN
Profondeur (m)	Depth (m)
Vitesse	Speed
Accélération	Accelerating
Virage	Turning
Motomarine (90 hp)	Personal watercraft (90 hp)
Ponton (90 hp)	Pontoon boat (90 hp)
Temps	Time
Nombre de coup	Number of pings

Figure 10 shows that high-performance personal watercraft (90 hp) do not impact the water column any more than their older, less powerful 70-hp counterparts (Figure 9). Although the intensity of the disturbance is greater during acceleration and turns, it still does not affect the water column at depths greater than 1.5 m. The more powerful pontoon boats (90 hp) also impact the water column at depths of up to 2 m.

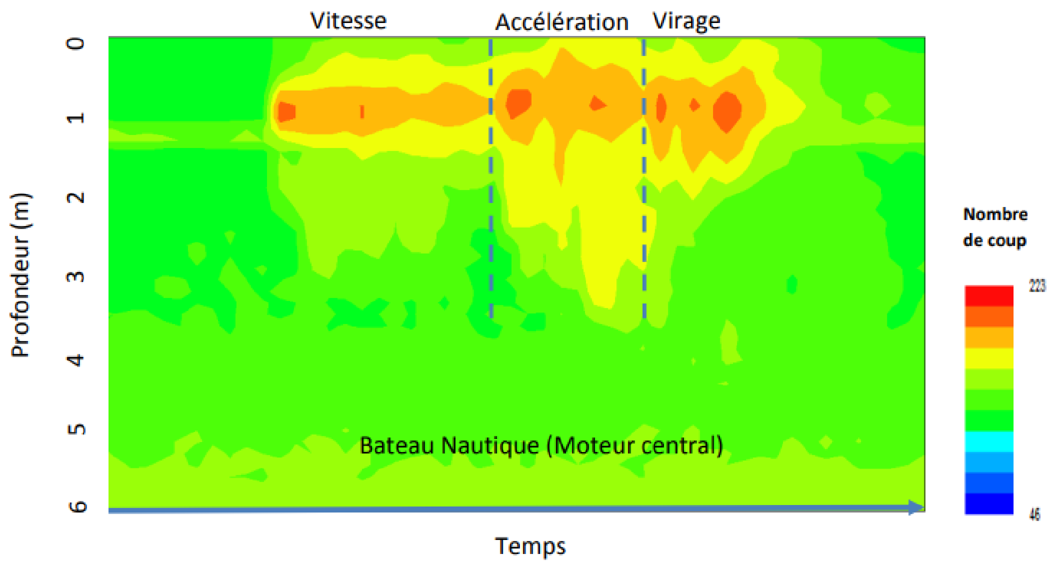


Figure 11: Impact of middle-engine water sports boats by operating mode

FR	EN
Profondeur (m)	Depth (m)
Vitesse	Speed
Accélération	Accelerating
Virage	Turning
Bateau Nautique (Moteur central)	Water sports boat (middle engine)
Temps	Time
Nombre de coup	Number of pings

As shown in Figure 11, middle-engine water sports boats impact the water column to depths of 1.5 m during straight-line passes at typical operating speeds, like the other vessels. However, when these vessels accelerate, they cause a significant disturbance at depths that can exceed 3 m. When turning, these boats cause a disturbance to the water column at depths as great as 2 m.

Together, these results show that the vessels using the lake do not impact the water column at depths of over 2 m, with the exception of water sports boats with a rear or middle engine while accelerating. The last type of vessel to be tested was the one that has caused the most controversy, the wake boat. Wake boats are powerful vessels designed specifically to generate the highest possible waves. These boats have a ballast system that can be used to change the vessel trim and the shape of the wave produced behind the boat (stern wave). Given their environmental impact and importance, wake boats are discussed in a separate section below.

5.2.2. The special case of wake boats

Turning tests were not conducted for wake boats. The study aimed to reproduce as closely as possible the boating practices that take place on Lac Noir, and wake boats are generally driven in a straight line at medium speeds of about 20 to 24 km/h to generate the largest possible waves. For wake boats, the focus was more on the cumulative effects of passes in the same direction, to determine whether the disturbance caused by a pass could be amplified by the successive pass of another wake boat in the same direction. Acceleration was also tested in wake boats.

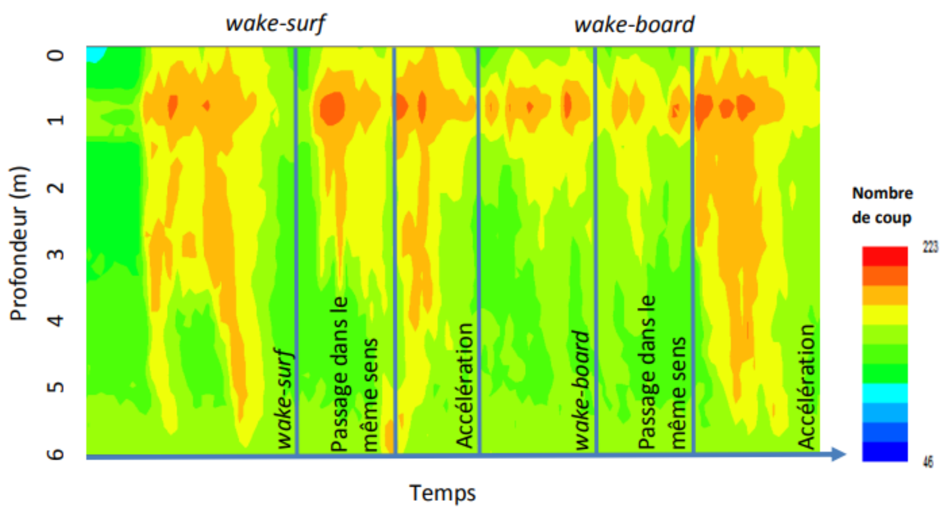


Figure 12: Impact of wake boats by operating mode

EN	FR
Profondeur (m)	Depth (m)
Temps	Time
Wake-surf	Wake surfing
Passage dans le même sens	Pass in the same direction
Accélération	Accelerating
Wake-board	Wake boarding
Nombre de coup	Number of pings

Figure 12 shows that the two practices (wake boarding and wake surfing) do not have the same impact on the water column. Wake surfing is by far the boating practice on Lac Noir with the greatest impact. Its impact was measured at depths as great as 6 m, which is twice the depth measured for accelerating water sports boats. No particular cumulative effect on disturbance was found for successive wake surfing passes in the same direction, although a greater disturbance could be observed at a depth of 6 m. Wake surfing also had a significant impact when the vessel was accelerating, affecting the water column at depths as great as 6 m. In contrast, for wake boarding, the impacts only reached depths of 3 m, whether involving passes in the opposite direction or in the same direction. However, during acceleration, wake boarding generated quite a significant impact on the water column, with disturbances observed at a depth of nearly 6 m. Therefore, during acceleration, vessel power is correlated with the depth impacted (Figure 13, R^2=0.98).

In short, the impact of wake surfing and wake boarding on the water column in Lac Noir is unequalled by that of other types of vessels.

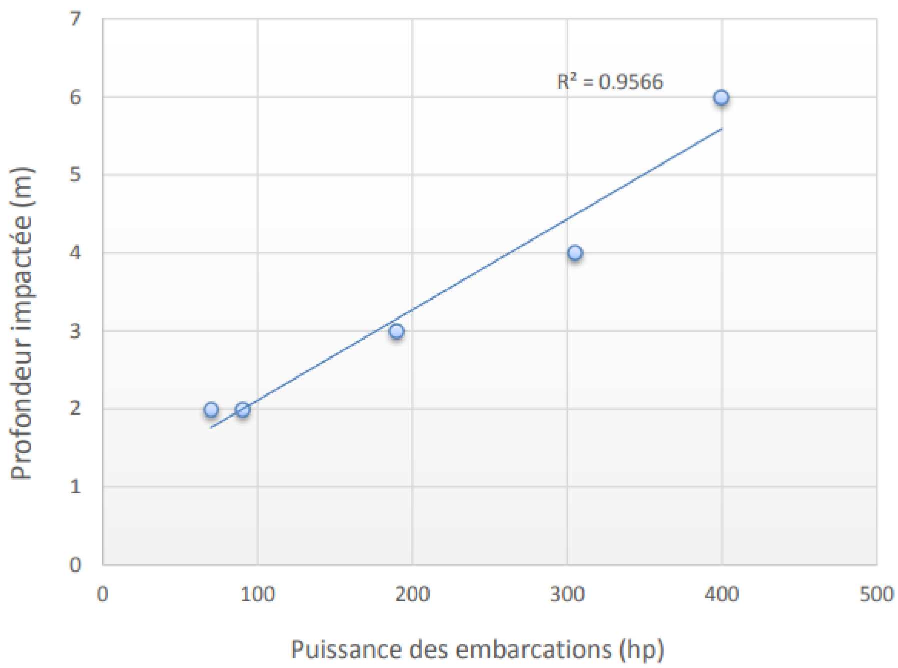


Figure 13: Vessel horsepower as a function of the depth impacted during acceleration

EN	FR
Profondeur impactée (m)	Depth impacted (m)
Puissance des embarcations (hp)	Vessel horsepower (hp)
R^2 = 0.9566	R^2 = 0.9566

6. Discussion

6.1. Water quality

Data collected at each station by the Voluntary Lake Monitoring Network were integrated in the project, making it possible to classify Lac Noir as mesotrophic. The lake is at an intermediate stage of eutrophication. Water quality is closely related to sediment quality, and the sediments in Lac Noir are a reservoir of nutrients with potential for resuspension. Considering the trophic status of the lake, MDDELCC (Quebec Department of Sustainable Development, Environment, and the Fight Against Climate Change) recommends that measures be undertaken to limit the input of nutrients from human activities. If limiting the input of nutrients is essential, preventing those already present from "reactivating" seems just as essential.

As for the physicochemical parameters, pH values lower than 6 must be monitored. The measurement of pH is crucial because this parameter influences the lake's biodiversity. Aquatic organisms require a pH of 6 to 9 to ensure their survival and proper development. Otherwise, pH-tolerant algae may be favoured, which could lead to massive blooms and exacerbate eutrophication. In addition, most physicochemical reactions are controlled by pH, including precipitation, dissolution and adsorption. pH values also play a critical role in pollution. For example, low pH values may promote the solubility of trace metal elements, which could increase their immediate bioavailability.

At Lac Noir, some trace metal elements can be found in high concentrations, namely cadmium, zinc and lead. Cadmium is found naturally in Quebec soils in average concentrations of about 1.20 ppm, while heavy metals occur in the lowest natural concentrations. However, in the presence of Ca, Co, Cr, Cu, Ni and Pb, the cation effect may also play a role in inhibiting adsorption and promoting the release of Cd. The average concentration of lead in Quebec soils is about 45 ppm, which is well below our results. Zinc has a baseline of about 113 ppm in Quebec soils, which is also lower than the concentrations measured in Lac Noir sediments. Zinc tends to form complexes with carbonates and iron and manganese oxyhydroxides, as well as adsorbing to the surface of clay minerals and organic matter.

In terms of metal pollution, a number of chemical speciation studies have shown that trace metal elements display various degrees of affinity for organic compounds, which is a key factor in their immediate and potential availability. Some elements (Hg, As, Sb, Pb, Cd and Zn) show a high affinity for organic matter, while others (Al, Cr, Co, Fe and Mn) show little tendency to be adsorbed to the organic fraction (El Bilali et al. 2002). These metals can come from multiple sources. Special attention must also be paid to Cd, Cu, Pb and Zn because these metals are usually present in road runoff (Morteau 2011). Although the source of these heavy metals has not been specifically studied, the literature can provide us with relevant clues about their source, which is largely road runoff. Table 9 shows the typical uses of Cd, Cr, Cu, Ni, Pb and Zn and their potential sources.

Table 9: Uses and potential sources of trace metal elements (adapted from Kabata-Pendias and Mukherjee 2007 and Galvez-Cloutier and Lefrançois 2005a).

Trace metal element	Typical use	Potential sources
Cd	Batteries, paint, plastics, plating, metal alloy manufacturing	Road paints, metal residue from trucks and cars
Cr	Metallurgical, chemical, paper and electroplating industries	Road paint, metal residue from trucks and cars (septic tanks in the past)
Cu	Quite vast: production of conductive materials for the electrical, motor and automobile industries, in bronze and brass alloys. Also present in fertilizers and pesticides.	Metal residues from trucks and cars (agriculture in the past and the present)
Ni	Mining industries	Metal residues from trucks and cars
Pb	Global trend of decreased production; batteries and ink, formerly in gas and paint	Metal residues from trucks and cars
Zn	Metallurgical (corrosion protection), chemical (rubber, paint), automotive (pipes, batteries), pesticides, plastics	Road paints, metal residues from trucks and cars (agriculture in the past and present)

At Lac Noir, the concentrations of Cd, Pb and Zn found are therefore not only of natural origin but very likely also of anthropogenic origin (i.e., linked to human activity).

Soluble phosphorus (in µg/L) is a nutrient stemming from non-point sources of pollution in the lake's watershed. Soluble phosphorus is bioavailable to primary producers in the aquatic environment such as plants, algae and cyanobacteria. An environment's trophic status can be determined in part from the soluble phosphorus concentrations present.

In the case of phosphorus, its sorption in sediments is one of the key processes regulating its mobilization and dynamic behaviour. Mobilized phosphorus can be re-adsorbed by other sediment components or released in the water. The adsorption or release process depends mainly on the composition of the sediments (e.g., organic matter, oxides) and phosphorus saturation. In general, the presence of organic matter is positively correlated with phosphorus adsorption (Tang et al. 2014).

Exogenous non-point sources are a function of the areas drained by runoff and leaching, and are more difficult to identify and control than point sources. They can result from the alteration of igneous rock and soil, land-use changes affecting atmospheric inputs, decomposing organic matter, fertilizers, detergents and drainage water from eroded land (Bergeron et al. 2002; Pilote et al. 2002).

6.2. Potential consequences of sediment and phosphorus resuspension

The issue of sediment resuspension is central to this study. Sediments are a collection of particles that are deposited by gravity (sedimentation) and have the ability to adsorb nutrients and heavy metals, which is why sediment resuspension is harmful to the environment.

Phosphorus tends to adsorb easily to soil particles in large quantities. Even if external phosphorus inputs were eliminated, phosphorus could continue to be released from the internal load in lake sediments for a period of 10 to 20 years (Sondergaard et al. 2003). It is generally believed that the phosphorus involved in lake metabolism is located in about the upper 10 cm of sediment. However, the mobility of phosphorus has been observed at depths ranging from 20 to 25 cm (Sondergaard et al. 2003). In general, phosphorus tends to adsorb to sediments during the winter and is partially released during the spring and early summer (Sondergaard et al. 2003). The exchange of phosphorus between sediments and the overlying layer of water (also known as the active layer) is a major component of the phosphorus cycle in natural aquatic environments, and depends on a number of physical, chemical and biological factors (Wetzel 2001).

Among the physical factors, the force of the wind can cause the resuspension of sediments in lakes, mainly in shallow water bodies. In some shallow lakes, wind may even be the main element controlling internal phosphorus loading. The resuspension of sediment can generate enough disturbance to release the P stored in sediment to the water column (Nedohin and Elefsiniotis 1997). This release can take less than 2 hours; whereas, the opposite phenomenon is much longer and can exceed 20 hours (Yousef et al. 1980).

This time difference allows phosphorus to be available long enough to cause increased algal growth and the degradation of water quality. Other factors can influence resuspension such as temperature, oxidation-reduction potential, pH and the iron/phosphorus ratio.

The rate of eutrophication can be accelerated by boating practices that impact the water column. Several studies have shown significant impacts caused by recreational boating activities, but the increasing number of vessels present, as well as the presence of more powerful vessels, tends to hasten the process even further. The density of vessels on a lake affects flow by promoting sediment resuspension (Mercier-Blais and Prairie 2014; Verney et al. 2007), resulting in increased turbidity (Alexander and Wigart 2013; Anthony and Downing 2003). McConchie and Toleman (2003) measured a 24% increase in the concentration of suspended solids in the water column related to vessel passes.

According to De Santiago Martin et al. (2016), turbidity can be increased by up to twice as much after a normal day of boating on a lake (< 74 trips) and by up to 12 times as much after a busy day (> 355 trips) (Alexander and Wigart 2013).

In addition to the growing number of vessels, there has been keen interest in new water sports in recent years, the impacts of which are beginning to be increasingly documented. Wake surfing and wake boarding promote the use of very powerful vessels (over 350 hp) travelling at medium speeds (24 km/h). These medium speeds are considered to be the most harmful by Anthony and Downing (2003), who estimate that vessels generate higher turbidity at medium speeds of 10 to 14 mph (18 to 24 km/h) compared with lower or higher speeds (5 mph or 30 mph). Raymond and Galvez-Cloutier (2015) found that wake surfing and wake boarding impact the water column to depths of 4 to 5 m, producing sufficient speeds to resuspend particles 50 µm in diameter.

The dimensionless Yalin-Shields diagram, Figure 14, was used in a river sedimentation study (Van Rijn 1989).

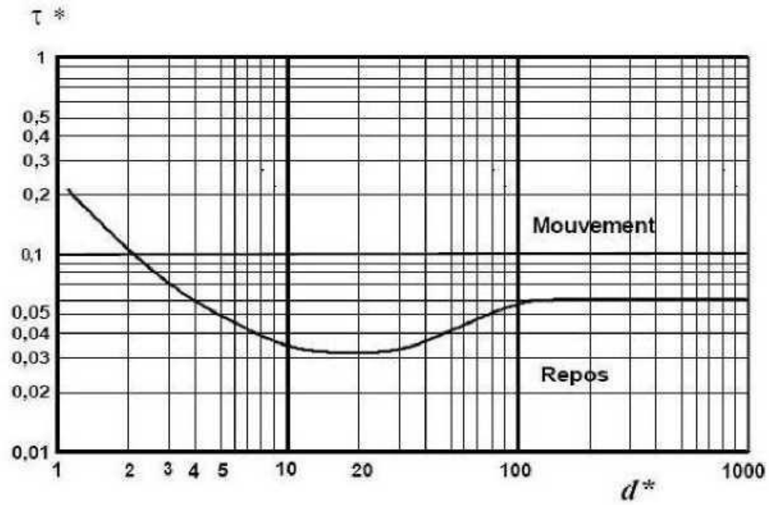


Figure 14: Dimensionless Shields diagram (Van Rijn 1989)

EN	FR
Mouvement	Motion
Repos	Rest

The Yalin-Shields diagram gives the value of the Shields parameter tau* (quantifying the critical shear stress) as a function of the value of d* (these two quantities are dimensionless). In this study, d*= 50 and tau*critical= 0.04, which results in a minimum speed for sediment resuspension of 3 mm/s. Raymond and Galvez (2015) demonstrated that water velocities of over 10 mm/s were generated deep in the water column by passing wake boats.

Therefore, the transport of particles potentially occurs at a depth of 6 m.

After vessels pass, the increased turbidity is greater in the lower layers of the water column over fine-textured bottom sediments (silts and clays) (Ailstock et al. 2002). Sediments can be transported more than 50 m from the vessel’s route (Lenzi et al. 2005). In 2014, Mercier-Blais and Prairie demonstrated that the waves produced by wake boats must travel a distance of 300 m or more (600 m in total) on either side of the wake for the energy generated by the wake to dissipate completely, which can lead to sediment resuspension and accelerated bank erosion. The resulting wave action and turbulence obviously lead to the resuspension of sediments and release of nutrients and pollutants into the water column (Alexander and Wigart 2013; Bastien et al. 2009; Gélinas et al. 2005; Wang et al. 2009; Zoumis et al. 2001), which has an impact on water quality.

Considering the depth of Lac Noir as shown on the bathymetric chart (Figure 3) and the grain size of the sediments present, it is evident from the results of this study that wake boarding activities cannot be practised in Lac Noir without consequences on the aquatic environment.

Impacts related to boating are mainly divided into three categories: physical, chemical and biological (De Santiago Martin 2016). These impacts,which occur in general in recreational boating, are intensified in the case of wake boats.

The impacts on Lac Noir may be harmful on several levels:

- ✓ Environmental:
  - Deterioration of water quality
  - Decline and change in aquatic populations
  - Growth of cyanobacteria
  - Growth of invasive plants

- ✓ Health:
  - Risks of metal bioaccumulation in aquatic species can pose a threat from the long-term consumption of these species.
  - In the case of Lac Noir, the situation is not alarming, but monitoring and follow-up are required to reduce the risk of these metals being released into the water column.

- ✓ Economic: significant socio-economic consequences resulting from the degradation of water quality:

  - The use and value of riparian areas are adversely affected, resulting in losses for users.
  - Loss of recreational activities = fewer tourists = less consumption = economic losses for businesses near the lake
  - Residents' quality of life and relationship with the environment are affected by the loss of recreational uses.

The environmental, economic and health consequences are closely interconnected and can be described as the direct, indirect and cumulative impacts of the practices of wake surfing and wake boarding. Therefore, it is important to understand that, in the current context of sustainable development, the environmental, economic and social impacts cannot be separated. Consequently, an integrated approach to the short-, medium- and long-term management of these impacts must be adopted.

6.3. Moving towards integrated management based on the minimization of impacts

The existing regulations (e.g., speed limits, distance from shoreline) have lagged behind the changes in vessel types and horsepower and the motorized water sports practised, and are insufficient to address these changes. The legislation must also evolve and be strengthened to align with the current reality.

Several factors influence the impacts of recreational boating, which can be categorized as factors related to vessel type and factors related to the lake environment.

The integrated management of boating must therefore address all of these factors in order to define new regulations. Based on this study and the literature, the following factors could be considered as suggestions or food for thought for sound management:

- ✓ Climate context:
  - During wind events, it would be best to limit motorized water sports and boating activities or even cancel them to prevent the cumulative impact of disturbances.
  - After wind events, it would be best to allow the lake to rest for at least 24 hours to promote sedimentation and limit the release of phosphorus.
- ✓ Morphological context: Levels of turbidity caused by vessel traffic are generally more pronounced in shallow water, so water depth is an important influential factor to be considered in establishing regulations to reduce impact (Hilton and Phillips 1982).
  - No activity involving wake boats should take place if the following requirements are not met: depth of at least 7 m and minimum width of 600 m (Mercier-Blais and Prairie 2014).
  - No activity involving water sports boats with middle or rear engines should take place if the following requirement is not met: depth of at least 5 m.
  - No activity involving pontoon boats or personal watercraft should take place if the following requirement is not met: depth of at least 2 m.

    - For all depths under 2 m, vessels should operate at the slowest speed possible and accelerate in a slow and gradual manner.

Anthropogenic factors related to motorized water sports and boating activities can also be regulated:

- ✓ Vessel density: The number of vessels on the lake should not exceed the recreational carrying capacity (De Santiago Martin 2016) of the lake. Once this is reached, access to the lake should be limited (closure of the docking area) or boating time should be limited to order to better share the lake.
- ✓ Vessel behaviour:
    - Limitation of movements: A large proportion of the vessel traffic may be caused by just a few vessels passing through the same point several times.
    - Vessel design:
        - Limit vessels according to size: The vessel size increases wake amplitude and energy by up to 10 times (Hill et al. 2002), as well as increasing the amount of suspended solids in the water column (Garrad and Hey 1987).
        - Hull: type of hull: Vessels with V-shaped hulls can produce waves 66% higher than vessels with flat-bottom hulls (Maynord 2001)
        - Power
        - Number of passengers: 5 to 6 passengers produce up to 22% more wave energy than 3 passengers.
    - Compliance with rules and speed limits: A linear relationship is not observed between vessel speed and maximum wave energy (Ahmad et al. 2011). The highest wave energy caused by the vessel or physical impact is observed at moderate speeds, such as 10–20 mph (Mercier-Blais and Prairie 2014), 6–18 mph (Raymond and Galvez-Cloutier 2015), 5–13 mph (Beachler and Hill 2003), or 9.2 mph (Ahmad et al. 2011).

If we apply some of these principles to Lac Noir, it appears that no part of the lake can accommodate wake surfing and wake boarding (Figure 15). Water sports boats with middle engines could operate in a limited area, while other boating activities (personal watercraft, pontoon boats) could be practised in a larger area. Motorized water sports and boating activities would not be allowed in areas near the shore or in Baie des Bounadère; however, navigation at low speeds without sudden acceleration could be acceptable. These limitations could also be extended to Rivière Noire, where low-speed and acceleration-free navigation could be recommended.

With a view to the sustainable management of aquatic ecosystems, Professor Galvez's team, through Dr. De Santiago Martin, have developed a decision-making tool for the selection of appropriate measures. This study corresponds to one of the phases of their decision-making process. This tool is particularly helpful due to the three independent and complementary phases it proposes for decision making.

This **decision support tool (DST)** is a guidance tool, procedure or analysis that can be used to help support decision making. A DST allows the effects of uncertainty to be addressed quantitatively and provides a structured process in which all hypotheses, model parameters and predicted results can be reviewed, modified and documented (De Santiago Martin 2016).

This DST was developed as a decision tree consisting of several phases:

- ✓ **Phase 1 – Recreational carrying capacity**
- ✓ **Phase 2 – Vessel traffic**
- ✓ **Phase 3 – Specific vessel**

The proposed study on Lac Noir falls within Phase 3 of the DST and makes it possible to identify the essential elements required for the sound and reasoned management of motorized water sports and boating activities, in the context of preserving the environmental and recreational activities.

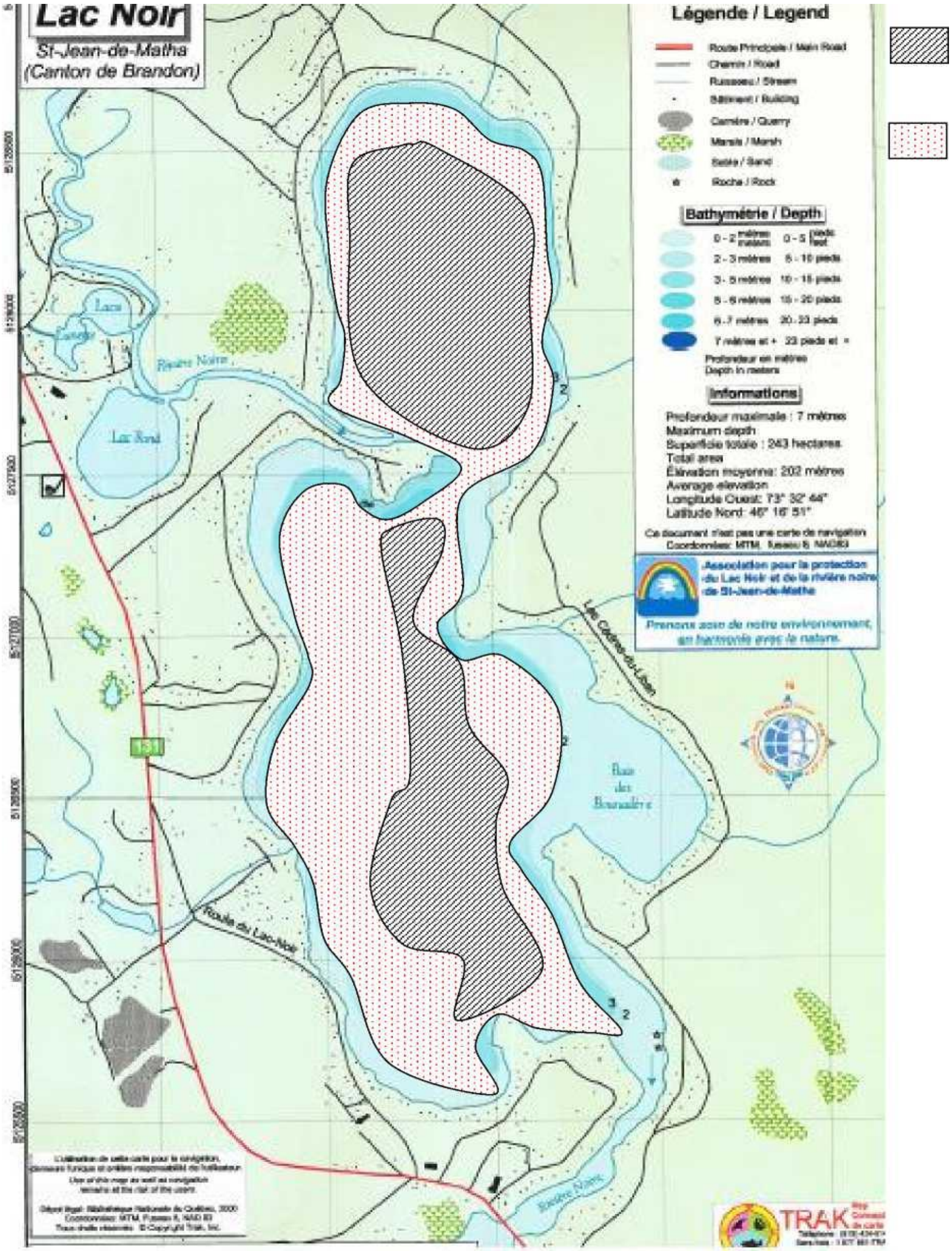


Figure 15: Delineation of areas open to specified boating activities on Lac Noir

7. Conclusions and outlook

The objectives of this study were to determine the quality of the bottom sediments in Lac Noir in order to determine the potential impact of motorized water sports and boating activities on water quality, and to make recommendations for the preservation of the lake. Lac Noir is a shallow lake that hosts a wide variety of boating activities, ranging from kayaking to the relatively new sports of wake boarding and wake surfing. Wake surfing generates large waves, with the resulting wave energy only dissipating after travelling 300 m horizontally and 6 m vertically. These statistics clearly indicate that these practices have a major environmental impact on sediment suspension and resuspension in the water column. Given the dimensions of Lac Noir and the requirements for wake boarding, it appears that this sport cannot be practised on Lac Noir. Quebec has a multitude of lakes of different sizes and characteristics. Therefore, wake boarding can be done on other lakes of a more suitable width and depth. In view of this study's results, these practices, depending on the sport, must be regulated, restricted or prohibited to avoid irreparable impacts on water quality and the aquatic environment.

The sediment quality results show that Lac Noir's bottom sediments are non-cohesive and very fine, and thus easily mobilized. Moreover, these sediments contain large amounts of phosphorus and certain heavy metals. The high phosphorus load could lead to the development of cyanobacteria (algal) blooms, a public health risk that is increasingly present in Quebec lakes, as well as issues with the bioaccumulation of heavy metals. Although Lac Noir is currently considered a mesotrophic lake by MDDELCC, its quality could deteriorate rapidly if motorized water sports and boating activities are not controlled.

Prevention is the most effective approach to reduce environmental problems. Given the potential impact of motorized boating on aquatic ecosystems, boating activities must be properly managed. In order to balance the need for environmental preservation and recreational uses, management strategies must be established based on scientific data and results.

Acknowledgements

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8. References

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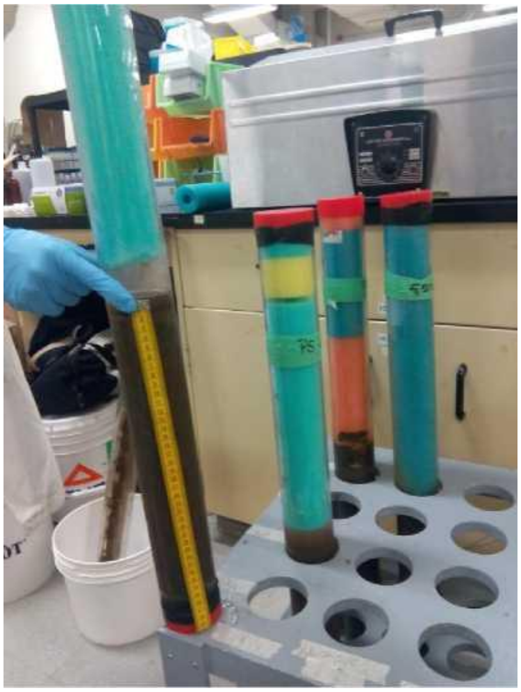
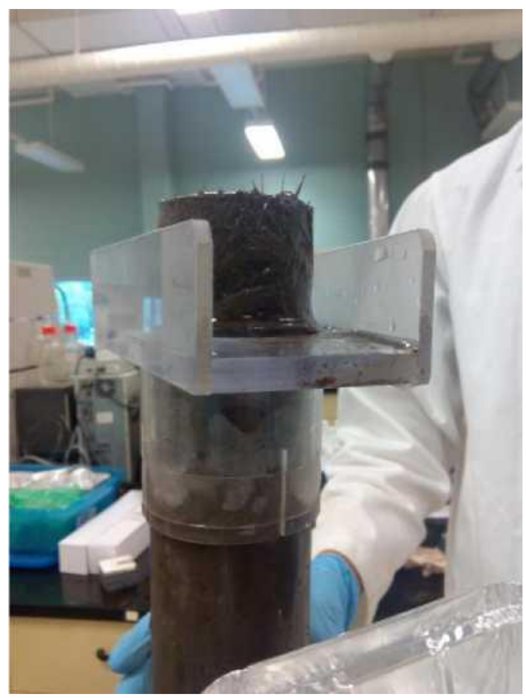
Appendix 1: Sediment samples in the laboratory



- ✓ Sediment core taken from Lac Noir



- ✓ Cores sectioned in 5 cm to 10 cm slices for analysis

✓ Dry samples for analysis

Appendix 2: Vessels tested during the study

		✓ GLASTRON water sports boat: 190 hp rear engine
✓ 22-foot pontoon boat, 90 hp.		✓ 

		✓ MASTERCRAFT water sports boat: 305 hp middle engine
✓ 18-foot pontoon boat, 25 hp		✓ 

		✓ BOMBARDIER jet-drive high-performance personal watercraft, ± 90 hp
✓ ARCTIC CAT jet-drive conventional personal watercraft, 70 hp		✓ 

		✓ MOOMBA wake boat for wake boarding and wake surfing: ± 400 hp rear engine