How to manage mercury at hydropower reservoirs

F. Bilodeau, M. Plante and A. Tremblay, Hydro-Québec, Canada

The development of new hydroelectric dams can result in a temporary increase in mercury levels in reservoir fish. During the past 40 years, Hydro-Québec has developed various strategies to prevent any mercury-related health risks for fish consumers. For the Romaine complex project, a risk assessment method was used to assess risk in three local populations. It showed that the project would not result in additional risks to fishers' health and was deemed satisfactory by Health Canada. Nevertheless, a mercury monitoring programme was set up to validate these predictions and communication tools were, and continue to be, distributed in these communities.

In Canada, hydroelectric generating stations account for roughly 60 per cent of the country's generating capacity. Hydro-Québec is one of the country's largest electricity producers, with an installed capacity of almost 36 800 MW. Hydro-Québec's hydroelectric generating fleet consists of 63 generating stations, 28 large reservoirs with a storage capacity of 176 TWh, and 681 dams and flow control structures.

Since the late 1970s, Hydro-Québec has studied the mercury issue in both natural and modified environments, owing to the potential health risks to reservoir fish consumers. Reservoir impoundment results in a significant but temporary increase in fish mercury (Hg) levels, a phenomenon that has been documented in many locations around the world [Bodaly *et al*., 2007[1]; Porvari, 1998[2]; Li and Xie, 2016[3]]. The increase is related to the decomposition of flooded organic matter such as ground cover, leaves, and mosses, which stimulates methylmercury (MeHg) production. MeHg is biomagnified as it passes through the aquatic food chain, moving from plankton (tiny small and microscopic aquatic organisms) to insect larvae to fish, where substantial concentrations may occur. Consumers of reservoir fish may therefore be more exposed to this contaminant.

In the La Grande complex reservoirs in the northern part of the province of Québec, Canada, fish mercury (Hg) levels have increased by factors ranging from 2 to 8, relative to those measured in natural environments. It has taken 10 to 31 years for these levels to return to values equivalent to those found before impoundment [Bilodeau *et al*., 2017[4]]. Nevertheless, fish from both natural environments and hydroelectric reservoirs can be eaten safely by following consumption guidelines based on the specific species and where it was caught (see fish consumption guides available on the Hydro-Québec website).

Numerous studies have been conducted to try to find mitigation measures to reduce this impact at the source. Land clearing, the stripping of forest soils and the controlled burning of organic matter before reservoir impoundment, as well as adding selenium or lime, and intensive fishing after reservoir impoundment, have all been studied [Sbeghen and Schetagne, 1995[5]; Surette *et al*., 2006[6]; Mailman and Bodaly, 2006[7]; Mailman *et al*., 2006[8], 2014[9]]. To date, none of these measures has been adopted for many reasons, including uncertain efficacy, adverse effects on aquatic fauna, and lack of technical and economic feasibility.

For Hydro-Québec, the most effective way of managing potential mercury-related risks to fish consumers after reservoir impoundment is to implement a risk management programme. The objectives of the programme are to ensure that fish consumers' Hg exposure remains below the thresholds for health effects recognized by public health authorities, while encouraging fish consumption for its nutritional value and health benefits. The strategy has evolved over the decades, and this article describes the most recent approach implemented in the context of the Romaine complex project.

1. Romaine hydroelectric complex

The Romaine hydroelectric complex, with an installed capacity of 1550 MW, is located in the boreal region of Québec, Canada, roughly 1000 km northeast of Montréal (see Fig. 1). It has four canyon-type reservoirs, with a total flooded area of around 220 km^2 (see Table 1). The Romaine region watershed is dominated by coniferous forests and thin podzolic and peat soils. The aquatic systems in the region are oligotrophic and relatively unproductive, with cold, well-oxygenated waters. The hydrology of the reservoirs reflects the region's climate, characterized by highly seasonal runoff with high flows in spring and low flows in late winter.

The Romaine 1, Romaine 2 and Romaine 3 reservoirs were impounded in 2015, 2014, and 2017, respectively, and the impoundment of Romaine 4 is expected in this year (Table 1).

Table 1: General characteristics of Romaine complex reservoirs

Reservoir	Impoundment (year)	Land area flooded (km^2)	Surface area at max. water level (km^2)	Total reservoir volume (× 10^9 m^3)	Average water residence time in reservoir (days)	Installed capacity (MW)
Romaine 1	2015	7	12	0.147	6	270
Romaine 2	2014	71	85	3.72	158	640
Romaine 3	2017	31	37	1.878	97	395
Romaine 4	2020*	111	144	2.71	171	245
Total	-	220	278	8.455	N/A	1550

*Anticipated year of impoundment.

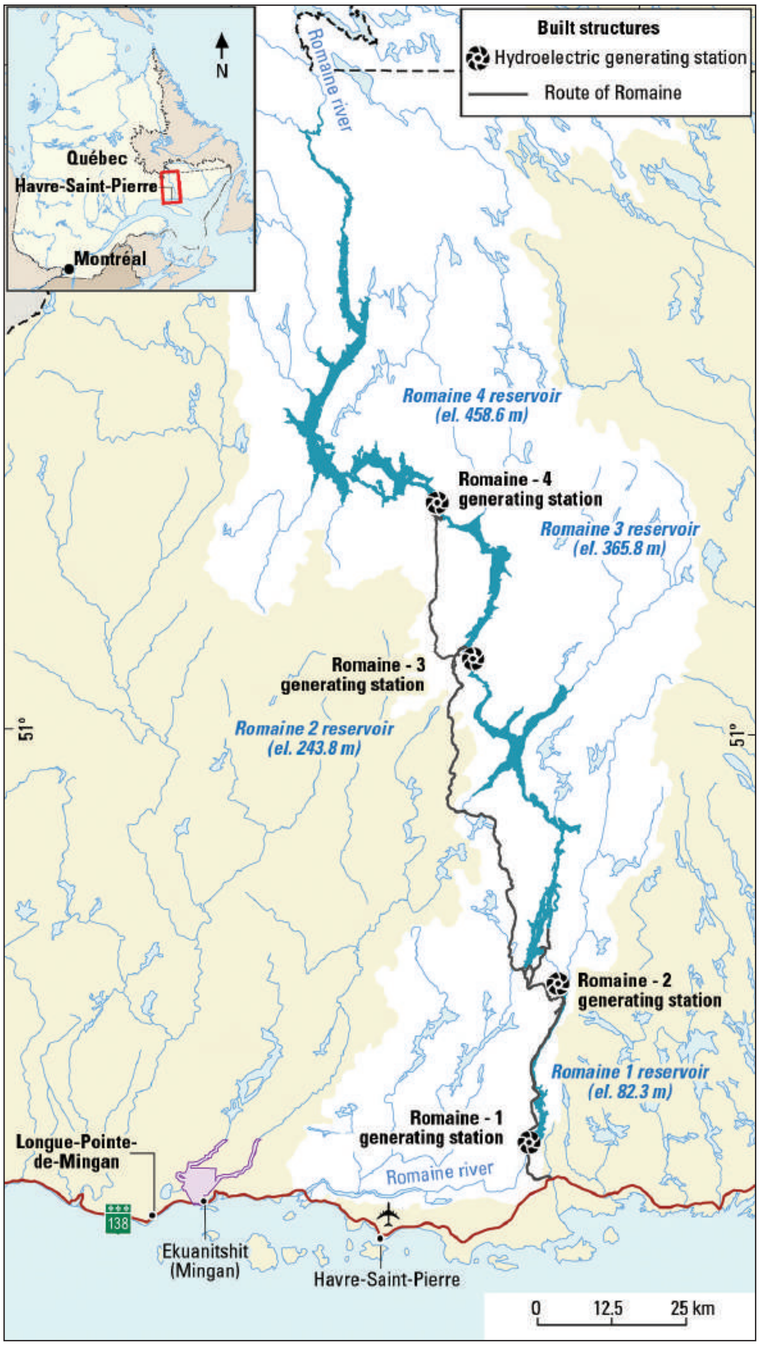

Fig. 1. The Romaine hydroelectric complex and nearby communities.

In the analysis of potential mercury-related risks, three local populations were studied, as they were likely to be affected by the project: the Innu community of Ekuanitshit (Mingan) and the non-indigenous populations of Havre-Saint-Pierre and Longue-Pointe-de-Mingan (see Fig. 1). These three communities are located downstream of the complex, less than 60 km from the Romaine-1 generating station. Community members can also fish along the coast of the Gulf of St. Lawrence, as well as in lakes and rivers near their communities.

2. Risk analysis for the Romaine complex

The risk analysis conducted for the Romaine hydroelectric complex involved: determining communities' Hg exposure before reservoir impoundment, Hg sources in their diet, and the proportion of the current sources of Hg in their diet that will be affected by reservoir impoundment; estimating future Hg exposure according to anticipated increases in Hg levels in the sources affected by reservoirs, taking account of various credible consumption scenarios; and, evaluating the additional health risk by comparing future exposure levels with the limits recommended by public health authorities.

2.1 Exposure before reservoir creation

In 2006, hair samples were collected for the analysis of total Hg to determine exposure in the Innu of Ekuanitshit population (36 hair samples), and in the communities of Havre-Saint-Pierre (94 samples) and Longue-Pointe-de-Mingan (60 samples). At the same time as hair samples were collected, a questionnaire on eating habits was carried out. This survey procedure had been approved beforehand by an independent health research ethics committee (IRB Institutional Review Board Services); an interpretation of the results was presented during public hearings on the project. The target groups studied included the general population, men, women, fishers, non-fishers and women of child-bearing age (18 to 39 years).

The communities' exposure before the project was found to be low, with no Hg-related risk to health. The average Hg exposure values of the various target groups ranged from 0.2 to 0.5 $\mu g\ g^{-1}$ in the Innu population and from 0.3 to 1.0 $\mu g\ g^{-1}$ in the non-indigenous populations, while the Health Canada recommendations correspond to levels of 5 $\mu g\ g^{-1}$ in adults, and 2 $\mu g\ g^{-1}$ in women of child-bearing age and children (see Table 2).

The survey on resource consumption habits in the three populations revealed nine significant dietary sources of Hg (Table 3): fish, waterfowl (birds), seafood, and marine mammals. Only food components A (non-piscivorous fish), C (piscivorous fish) and F (waterfowl) from freshwater environments in the reservoirs and downstream areas were likely to be affected by the project.

The proportion of food components potentially affected by the project is estimated to be low: 3.3 per cent for the Innu of Ekuanitshit, 0.8 per cent for Havre-Saint-Pierre, and 0 per cent for Longue-Pointe-de-Mingan. The survey also revealed that the Romaine river is not used much for fishing and that the species preferred for sport and traditional fishing are those with low Hg levels such as brook trout (speckled or sea trout), salmon and capelin.

2.2 Future exposure after reservoir creation

The future Hg exposure of communities was calculated according to Eq. 1:

$$F\mathrm{Hg}_{exp} = I\mathrm{Hg}_{exp} * \frac{F[\mathrm{Hg}_{avg}]_{Diet}}{I[\mathrm{Hg}_{avg}]_{Diet}} \qquad ...(1)$$

where:

- $F\mathrm{Hg}_{exp}$ = Future Hg exposure (ppm in hair);
- $I\mathrm{Hg}_{exp}$ = Initial Hg exposure (ppm in hair);
- $F[\mathrm{Hg}_{exp}]_{Diet}$ = Future average Hg concentration in diet ($\mu g\ g^{-1}$); and,
- $I[\mathrm{Hg}_{exp}]$Diet = Initial average Hg concentration in diet ($\mu g\ g^{-1}$).

For each participant, the average Hg concentration in their diet was calculated according to Eq. (2):

Table 2: Hg exposure in local populations before creation of the reservoir in 2006 ($\mu g\ g^{-1}$ in hair)

Target group	Innu of Ekuanitshit			Havre-Saint-Pierre			Longue-Pointe-de-Mingan		
	N	Mean	Range	*N*	Mean	Range	*N*	Mean	Range
General population	36	0.5	0.1–2.0	94	0.9	0.1–4.1	60	0.7	0.1–7.4
Women (18–39 years)	13	0.3	0.1–0.6	25	0.6	0.1–2.3	9	0.3	0.1–0.6
Fishers	24	0.5	0.1–1.1	67	1.0	0.1–4.1	35	0.8	0.1–7.4
Women (18–39 years)	7	0.4	0.1–0.6	16	0.8	0.1–2.3	6	0.3	0.1–0.4
Non-fishers	12	0.4	0.1–2.0	27	0.5	0.1–1.7	25	0.5	0.1–1.8
Women (18–39 years)	6	0.2	0.1–0.4	9	0.3	0.1–0.7	3	0.4	0.2–0.6

$$[\mathrm{Hg}_{avg}]_{Diet} = \left(\sum_{i=A}^{I}\sum_{j=1}^{n}[\mathrm{Hg}_{xy}]\right) \div Nb_{meals} \quad ...(2)$$

where:

- $[\mathrm{Hg}_{avg}]_{Diet}$ = Average Hg concentration in diet ($\mu g\ g^{-1}$);
- $I = A$ to I sources of Hg;
- $J = 1$ to n meals consumed;
- $[\mathrm{Hg}_{xy}]$ = Hg concentration in x species from y location consumed ($\mu g\ g^{-1}$); and,
- Nb_{meals} = Total number of meals consumed.

Future concentrations in sources affected by increases in Hg caused by the project were determined using a semi-mechanistic model. According to the results of this model, reservoir impoundment will likely increase Hg concentrations in fish in reservoir sectors and downstream areas by a factor as high as 8 depending on the species [Hydro-Québec, 2007[10]]. For species in the affected areas, the following maximum values were used: 1.1 $\mu g\ g^{-1}$ for non-piscivorous fish; 2.78 $\mu g\ g^{-1}$ for piscivorous fish; and, 1.0 $\mu g\ g^{-1}$ for waterfowl.

Three scenarios that take into account consumption habits in communities, communities' perception of mercury-related risks and the projected use of reservoirs after the completion of the Romaine complex were used to determine future exposure:

- *Status-quo scenario*: No change in consumption habits, but predicted Hg concentrations in fish and waterfowl were applied to participants stating their intention to fish in the planned reservoirs using Eq. (2).
- *Realistic scenario*: 10 per cent of the meals of trout (non-piscivorous species) currently harvested from unaffected natural areas were replaced by meals of reservoir fish (70 per cent piscivorous species and 30 per cent non-piscivorous species).
- *Conservative scenario*: 25 per cent of the meals of trout (non-piscivorous species) currently harvested from unaffected natural areas were replaced by meals of reservoir fish, in the same proportions as in the realistic scenario.

Only the results for the conservative scenario, which is considered the worst-case scenario, are presented for the three local populations by target group (see Table 4).

The predicted future Hg exposures will likely remain below recognized thresholds for health effects, with average values ranging from 0.81 to 1.21 $\mu g\ g^{-1}$ for adults in general, from 0.75 to 1.41 $\mu g\ g^{-1}$ for fishers and from 0.44 to 0.90 $\mu g\ g^{-1}$ for women aged 18 to 39 years. A significant increase in mercury-related health risks will not occur in these populations. This risk analysis was evaluated by Health Canada at the request of the Joint Review Panel during its review of the environmental impact study for the project [Health Canada, 2008[11]]. Health Canada experts concluded that future levels of Hg exposure (obtained from the models)

Table 3: Proportion of significant sources of Hg in the diet of communities before reservoir creation in 2006

Source of Hg	Innu of Ekuanitshit (per cent)	Havre-Saint-Pierre (per cent)	Longue-Pointe-de-Mingan (per cent)
A: Non-piscivorous fish[(i)] from freshwater environments affected by the project	1.1	0.6	0.0
B: Non-piscivorous fish from freshwater environments not affected by the project	24.1	9.5	16.9
C: Piscivorous fish[(ii)] from freshwater environments affected by the project	2.0	0.2	0.0
D: Piscivorous fish from freshwater environments not affected by the project	5.1	1.2	1.2
E: Marine fish and seafood from natural environments not affected by the project	5.3	3.8	3.4
F: Waterfowl[(iii)] from environments affected by the project	0.2	0.0	0.0
G: Waterfowl from environments not affected by the project	39.6	0.9	0.7
H: Marine mammals (not affected)	3.2	24.4	5.8
I: Store and restaurant fish and seafood (not affected)	19.3	59.4	72.0
Total sources	100	100	100
Proportion of sources affected [(iiii)]	3.3	0.8	0

[(i)] Non-piscivorous freshwater fish from reservoirs and downstream areas: lake whitefish, suckers and brook trout; [(ii)] Piscivorous freshwater fish from reservoirs and downstream areas: northern pike and lake trout; [(iii)]Waterfowl: black duck, Canada goose, common eider and common merganser; [(iiii)] Only sources A, C and F will likely be affected by reservoir creation.

Table 4: Comparison of baseline and future Hg exposures ($\mu g\ g^{-1}$ in hair) in local communities based on the conservative scenario

Target group	Innu of Ekuanitshit		Havre-Saint-Pierre		Longue-Pointe-de-Mingan	
	Baseline exposure	Future exposure	Baseline exposure	Future exposure	Baseline exposure	Future exposure
General population	N = 36		N = 94		N = 60	
Average value	0.48	0.81	0.85	1.21	0.70	0.99
Minimum	0.10	0.10	0.10	0.10	0.10	0.10
Maximum	2.0	5.0	4.1	5.2	7.4	7.4
Fishers	N = 24		N = 67		N = 35	
Average value	0.51	0.75	0.99	1.41	0.82	1.18
Minimum	0.10	0.10	0.10	0.14	0.10	0.10
Maximum	1.1	2.1	4.1	5.2	7.4	7.4
Women (18–39 years)	N = 13		N = 25		N = 9	
Average value	0.28	0.44	0.63	0.90	0.33	0.48
Minimum	0.10	0.10	0.13	0.13	0.10	0.10
Maximum	0.57	1.3	2.3	4.7	0.62	1.1

would remain low and would not be a cause for concern in terms of human health. However, this conclusion is based on modelling, and assumes that the communication of risks and the environmental monitoring programme will be implemented after the project. Details on the latter are provided in the following sections.

3. Environmental monitoring

Although the health risk to local populations is not considered to be of concern, the establishment of an environmental monitoring programme after the project is essential to validate predictions and reassure local communities by taking measurements in the field. The measures in this programme include: monitoring the evolution of fish Hg concentrations until they return to levels that allow for the consumption of fish from reservoirs at quantities equivalent to recommendations for the region's natural environments; communicating the risks and benefits of fish consumption through the regular dissemination of information and the production of an updated fish consumption guide; monitoring Hg exposure in local populations; and, assessment of the effectiveness of the communication programme.

An agreement was reached with government authorities on the schedule of planned follow-up activities before the project began (Table 5).

Table 5: Schedule of environmental follow-up activities for the Romaine complex related to mercury

Activity	Follow-up years
Fish Hg levels	2017, 2019, 2023, 2026, 2028, 2031, 2035 and 2039
Development of customized communication tools and distribution to communities	Continuing and according to needs
Hg exposure in local populations (Hg in hair)	2023 and 2030
Efficacy of communication programme	2023

Taking a fish sample.

4. Communication with communities

The selection of appropriate communication tools with suitable content to inform local populations is a critical aspect of the programme. These tools are customized for each community and take account of residents' dietary habits. They are always produced in collaboration with public health authorities and First Nations representatives.

A number of evaluations of the various tools used by Hydro-Québec over the years have shown that the general message conveyed has often been viewed as confusing or contradictory [INSPQ, 2002[12]; Hydro-Québec Production and SEBJ, 2013[13]]. Given the low Hg exposure in the communities near Hydro-Québec's facilities, the decision was made to convey clearly and unequivocally in the communication tools used, the main message that fish and seafood are good for health and that communities can continue to consume them.

4.1 Fish consumption guide

A map-based guide to the consumption of local fish and seafood from the Romaine river was produced in 2019. As in all Hydro-Québec's tools, the basic criteria used to determine the consumption recommendations included in the guide are the tolerable daily intake (TDI) values established by the World Health Organization and Health Canada: 0.47 μg/kg/d for adults and 0.2 μg/kg/d for pregnant women and children. These recommendations are based on the predicted maximum levels (validated by the first fish Hg survey), and are approved by public health authorities before being disseminated.

Each consumption category is associated with a maximum number of meals per month and is illustrated in colour showing the safe number of meals by species and fishing site (see Table 6).

Table 6: Equivalence between fish THg concentrations ($\mu g\ g^{-1}$, wet weight) and general adult consumption guidelines

Mean total Hg concentrations in fish ($\mu g\ g^{-1}$)	Quantitative recommendations (maximum number of meals per month)
≤ 0.29	>12
0.30 to 0.49	8
0.50 to 0.99	4
1.00 to 1.99	2
2.00 to 3.75	1
>3.75	<1

Far left: Gillnet fishing.

Putting the fish sample in a Whirl-Pak-type bag.

Setting a gillnet in the Romaine river.

The calculation of the safe number of meals per month for each consumption category was based on the following: a 230-g portion of fish (before cooking), a body weight of 60 kg, a mean total Hg level in fish of a standardized length specific to each species, and regular consumption throughout the year. These recommendations are therefore very conservative.

4.2 Customized approach for pregnant women

The group at the greatest risk is pregnant women, as there is a need to protect the unborn child, for which the TDI is lower than in adults. With help from the Ekuanitshit health centre, Hydro-Québec developed a customized approach specifically for pregnant women. In this native community, a nutritionist meets with all pregnant women during their pregnancy. Several questions have been integrated in this consultation that aim to educate women about the benefits of fish and seafood consumption for the development of the unborn child. This also helps guide fishers' choice of species towards those with low mercury levels, illustrated by green circles in the guide (no restrictions on consumption).

If a woman expresses concerns about mercury, the health centre takes a hair sample according to an established protocol. The sample is then sent to a laboratory accredited to analyse mercury, with Hydro-Québec assuming all the costs of the procedure. The results are then sent to the attending physician and are communicated to the patient in a confidential manner. To date, no requests of this type have occurred.

5. Conclusion

Reservoir impoundment results in substantial, but temporary, increases in Hg levels in reservoir fish. This issue is observed around the world. There is no effective mitigation measure to eliminate this impact at the source. After more than 40 years of research on the issue, Hydro-Québec, in collaboration with health agencies and First Nations, has developed an effective approach for managing the potential mercury-related health risks to fishers and their families adequately.

In the context of the Romaine hydroelectric complex, a risk analysis on potential Hg exposure was performed for three local communities. The communities' Hg exposure before the construction of the project was found to be low, and well below the limits recommended by Health Canada. These communities were therefore not at risk and could continue to safely benefit from fish consumption. After the impoundment of the Romaine reservoirs, despite the significant increase predicted in Hg levels in reservoir fish and in fish from downstream areas, it was demonstrated that there were no anticipated additional health risks to fish consumers in the three communities.

The approach developed by Hydro-Québec to prevent all mercury-related health risks requires: monitoring the evolution of fish Hg levels after reservoir impoundment on a long-term basis; preparing communications tools adapted to local fishing practices and ensuring that they are understood by communities; and, offering the measurement of Hg exposure through hair analysis for individuals expressing concern about mercury. Collaborating with local public health authorities and First Nations is essential.

In the context observed in Québec, it has become imperative over time not only to maintain fish consumption, but also to encourage it. The approach developed by Hydro-Québec is designed to take account of cultural realities, consumption habits and the importance of hunting and fishing in each community. This approach demonstrates that hydroelectric development can be undertaken while adequately preventing potential mercury-related health issues. ◊

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F. Bilodeau


M. Plante


A. Tremblay

François Bilodeau graduated in chemistry (2000) and obtained is master degree in Water Sciences from Institut national de la recherche scientifique (INRS) in 2002. His work at Hydro-Québec, since 2007, has mainly been related to the dynamics of mercury and water quality in reservoirs and also, to environmental impact from the nuclear activities. He is the Mercury Programme Manager for Hydro-Québec.

Hydro-Québec, Environment Department, 800, boul. De Maisonneuve Est, 23e étage, Montréal, (Québec) H2L 4M8.

Dr. Michel Plante is a physician who graduated from University of Montreal in 1979. Since 1982, he is been a medical advisor for Hydro-Québec. He is in charge of the medical research program of Hydro-Québec and he is responsible for providing human health risk assessments and commissioning epidemiological and experimental studies on various topics including electromagnetic fields; methylmercury and ionizing radiation.

Hydro-Québec, Health and Safety Department, 75, boul. René-Lévesque Ouest, Montréal, (Québec) H2Z 1A4.

Dr. Alain Tremblay obtained a PhD in Environmental Sciences (1996) from the University of Québec in Montréal (UQÁM). His work at Hydro-Québec, since 1996, has mainly been related to the dynamics of mercury and greenhouse gases (GHG) in hydroelectric reservoirs. He is the GHG Programme Manager for Hydro-Québec.

Hydro-Québec, Environment Department, 800, boul. De Maisonneuve Est, 23e étage, Montréal, (Québec) H2L 4M8.