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4

Muskrat Falls, Methylmercury, Food Security, and Canadian Hydroelectric Development

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Hydroelectricity has substantially smaller carbon emissions than fossil fuel technologies while supporting electrical base load, unlike other renewables. However, development of hydroelectric reservoirs transforms terrestrial and aquatic ecosystems, altering biogeochemical processes and the structure of local food webs. Flooding and erosion of soils stimulates the production of methylmercury (MeHg), a potent neurotoxicant that bioaccumulates in food webs. In Canada, roughly half of existing hydropower capacity is located on land covered by Indigenous land claims agreements, while virtually all potential future capacity is located within 100 kilometres of Indigenous populations (Calder et al. 2016; Lee, Hanneman, and Cheng 2012).

Traditional Indigenous diets include large amounts of locally harvested fish and other seafood that are sensitive to increases in local methylmercury levels. Fish consumption advisories are the dominant strategy for defraying risks associated with elevated methylmercury levels (Hydro-Québec Production 2014; Passos and Mergler 2008; Shimshack and Ward 2010; Teisl et al. 2011). Such advisories can have complex and even adverse impacts on Indigenous health because traditional foods represent nutrient-dense components of Indigenous diets (Wheatley and Paradis 1996). Furthermore, traditional hunting and harvesting activities fulfill important psychosocial roles that interact with health in complex and poorly understood ways (Furgal, Powell, and Myers 2005). Increases in methylmercury production and accumulation in fish following flooding associated with hydropower development has been recognized for decades. However, there are many challenges inherent in forecasting the magnitude of contaminant exposures and balancing them against nutritional requirements and cultural preservation.

This chapter summarizes the prospective risk assessments for increases in methylmercury exposure associated with flooding of the Muskrat Falls hydroelectric facility on the lower Churchill River in Labrador, Canada.[5] We identify scientific and policy challenges associated with risk forecasting, mitigation, and overall decision-making. We start with a brief review of the science on hydroelectric development and methylmercury risks for Indigenous populations. We then summarize the scientific reviews carried out for Muskrat Falls by the Province of Newfoundland and Labrador, its Crown corporation Nalcor Energy and its consultants through the conclusion of the Joint Federal-Provincial Review Panel
(JRP) in 2011. We highlight the principal criticisms of these reviews made by federal reviewers and local Indigenous associations and governments. We then describe the research carried out between 2011 and 2017 by researchers at Harvard University in collaboration with Memorial University (Calder et al. 2016; Schartup et al. 2015). This research aimed to fill scientific gaps that had limited the interpretability of reviews carried out by Nalcor and its associates.

This research and associated policy reports published by the Nunatsiavut Government (NG) (Durkalec, Sheldon, and Bell 2016a, b), representing the Inuit of the Labrador Coast, contributed to public demand for mitigation of risks associated with methylmercury before flooding of the Muskrat Falls reservoir (Boone 2016; Breen 2017). In response, the Province of Newfoundland and Labrador convened an Independent Expert Advisory Committee (IEAC) to evaluate scientific evidence on risks associated with flooding of the Muskrat Falls reservoir and create recommendations for mitigation and monitoring. The IEAC recommended reservoir clearing and wetland capping to minimize risks prior to reservoir impoundment (IEAC 2018). The advice from the IEAC closely mirrored the recommendations of the JRP convened almost a decade earlier (Government of Canada and Government of Newfoundland and Labrador 2009) but did not achieve consensus among voting members. We summarize the activities of the IEAC here.

We close this chapter with observations on the lessons of Muskrat Falls for broader hydroelectric and other natural resource development in Canada. Jurisdiction for environmental review in natural resource decision-making is mostly provincial, and there is wide variability across Canadian provinces in the value assigned to (and political independence of) these processes. This case study adds to other research pointing to the need for politically independent institutions for science-based policy and mechanisms to ensure consultation and consent of Indigenous populations impacted by development are needed more broadly.

1. Hydroelectric Development, Methylmercury, and Indigenous Populations

Mercury (Hg) is released into the environment from both natural (e.g., volcanoes) and anthropogenic (e.g., coal-fired power plants) sources. It cycles globally through the atmosphere and can be deposited in remote ecosystems far from sources (Horowitz et al. 2017). In aquatic environments, microbes convert inorganic mercury to methylmercury (Compeau and Bartha 1984; Parks et al. 2013). Methylmercury production can be stimulated by factors that influence the activity of microbes that methylate mercury, such as availability of labile organic carbon and anoxic conditions. Methylmercury biomagnifies in food webs, reaching concentrations in large fish and marine mammals up to ten million times greater than the ambient water, making seafood the predominant contributor to population-wide methylmercury exposures in most countries (Clarkson 1993; Sunderland 2007). Methylmercury crosses the blood-brain and placental barriers, making it a potent neurotoxicant for the developing fetus (Debes, Weihe, and Grandjean 2016; Lohren et al. 2016).

The flooding required for creation of reservoirs mobilizes organic matter and inorganic mercury in soils and facilitates the creation of anoxic conditions most conducive to the activity of microbes that methylate mercury such as sulfate reducing bacteria (Hall et al. 2005). Prior work in Canada has reported that fish methylmercury levels peak within ten years after flooding and decline over a period of roughly thirty years (Bodaly et al. 2007; Schetagne and Verdon 1999; Schetagne and Therrien 2013). Differences in flooded area, soil carbon content, and other factors contribute to considerable difference in the magnitude of increase across environments (Hall et al. 2005; Jackson 1988). Available measurements suggest peak increases ranging from two- to eleven-fold beyond baseline conditions (Anderson 2011; Schetagne and Therrien 2013). Most available empirical data on post-impoundment methylmercury are for fish within newly created reservoirs, but limited available data suggest that impacts on the downstream environment are likely to be at least as high (Brouard, Doyon, and Schetagne 1994; Kasper et al. 2012; Kasper et al. 2014).

Elevated prenatal exposures to methylmercury have been associated with a range of neurological impacts ranging from attention and IQ deficits at lower exposures to mental retardation and cerebral palsy at higher exposures (NRC 2000). High methylmercury exposures have also been associated with cardiovascular risk factors, notably oxidative stress, atherosclerosis and decreased heart rate variability, and outcomes, notably myocardial infarction (Roman et al. 2011). There is no known safe dose of methylmercury, and increases in exposures below regulatory reference values have been associated with neurological impacts (Karagas et al. 2012; NRC 2000; Vejrup et al. 2018).

The United States Environmental Protection Agency (U.S. EPA) uses the concept of a "reference dose" (RfD) to describe the lifetime intake of a chemical (other than genotoxic or carcinogenic contaminants) that poses no appreciable increase in risk (U.S. EPA 1993). A variety of safety factors are used in risk assessment to ensure an adequate margin of safety between exposures and observed negative outcomes on health, as well as to account for sensitive populations and adjust for study quality. The current U.S. EPA RfD for methylmercury is 0.1 $\mu g\ kg^{-1}\ day^{-1}$ based on IQ impacts associated with prenatal exposures. There is now widespread agreement that this reference dose is too high, and consequently, it is currently being revised downward (U.S. EPA 2019). Health Canada uses the "tolerable daily intake" (TDI), a similar concept to the RfD. It derives a provisional TDI for methylmercury of 0.2 $\mu g\ kg^{-1}\ day^{-1}$ for women of childbearing age and children, and 0.47 $\mu g\ kg^{-1}\ day^{-1}$ for everyone else, using a different margin of safety than the U.S. EPA (Health Canada 2004).

Seafood consumption is higher among Indigenous than among non-Indigenous people in Canada, and so Indigenous people are particularly vulnerable to increases in environmental methylmercury levels (Chan and Receveur 2000; Wheatley et al. 1997). Across Canada, 131 hydroelectric facilities representing nearly 50 per cent of current installed capacity are located within Indigenous treaty or settled land claim areas, not counting facilities with downstream or indirect impacts on nearby communities (Lee et al. 2012). The role of hydro power in overall methylmercury exposures and human health risks has been difficult to determine because of incomplete baseline data and diets that change in response to food consumption advisories (Schoen and Robinson 2005). Limited available longitudinal data reveal that in some cases methylmercury exposures have decreased after hydroelectric development as increases in fish methylmercury have been outweighed by reduced intake of local foods (Cacchione 2017; Schetagne et al. 2010).

Food consumption advisories are the default policy response to increased methylmercury levels following hydroelectric development (Hydro-Québec 2014; Hydro-Québec Production 2014; Passos and Mergler 2008). While they have in many cases been associated with stable or even reduced exposures to methylmercury, the net impacts on health are unclear. Reduced intake of traditional foods has tended to exacerbate food insecurity and nutritional deficiencies (Johnson-Down and Egeland 2013; Laird et al. 2013; Sheehy et al. 2015). Efforts to promote consumption of low-methylmercury species and discourage consumption of high-methylmercury species in order to balance risks and benefits are not always successful. Food consumption advisories deployed in both Indigenous and non-Indigenous populations have had highly variable effects, in some cases failing to change behaviours and in other cases causing people to reduce seafood intake beyond the scope of the advisory (Furgal, Powell, and Myers 2005; McAuley and Knopper 2011; Shimshack et al. 2007; Verger et al. 2007; Wheatley and Paradis 1996).

2. Environmental Impact Assessment at Muskrat Falls

Labrador Indigenous communities have been affected by hydro-power-related methylmercury impacts since the development of Churchill Falls on the upper Churchill River in the early 1970s (Armitage 2007). The Churchill Falls hydroelectric project caused methylmercury levels to increase more than tenfold at their peak with impacts extending more than 300 kilometres downstream over a period of more than thirty years (Anderson, Scruton, and Payne 1995; Anderson 2011). These impacts extended into Lake Melville, an estuary (fjard) draining into the Atlantic Ocean. Lake Melville forms part of the Labrador Inuit Settlement Area and serves as traditional hunting and fishing territory for the Labrador Inuit, represented by the NG (The Inuit of Labrador et al. 2005). The NG is therefore concerned about the similar impacts from Muskrat Falls, which is only fifty kilometres upstream of Lake Melville.

The first environmental assessments for the Muskrat Falls project were coordinated by Nalcor Energy, a Newfoundland and Labrador Crown corporation in charge of project construction and operation, and included a risk assessment for methylmercury. Nalcor's initial assessments considered only fish in the Churchill River environment. Initial analysis suggested peak fish methylmercury levels 80 to 370 per cent above baseline levels across species, while allowing for increases up to 800 per cent beyond baseline levels in the uncertain event of substantial changes to the structure of the food web (Harris and Hutchinson 2008). The JRP considered increases 200 to 500 per cent above baseline levels (Government of Canada and Government of Newfoundland and Labrador 2011). Nalcor revised these estimates downward (increases ≤ 90% above baseline) following further modelling work (Harris, Hutchinson, and Beals 2010).

Nalcor's assessments categorically excluded Lake Melville, claiming that "there is no reasonable possibility that the Project would have an adverse environmental effect on the Labrador Inuit Settlement Area" (Nalcor Energy 2009). This claim was based on the rationale that the diluting effect of Goose Bay, between the Churchill River and Lake Melville, would bring any impact on Lake Melville to "within the range of natural variability" (Nalcor Energy 2011). However, natural variability for many parameters spans several orders of magnitude and can conceal large impacts on mean values in the absence of sustained sampling efforts (Sunderland 2011). Nalcor's models for mercury dynamics in the Churchill River and Lake Melville made extensive use of "default values" instead of site-specific data. A complete lack of local water and sediment mercury data made it extremely difficult to predict how the river and estuary were likely to respond to upstream flooding (Sunderland 2011). Fisheries and Oceans Canada noted that extensive use of professional judgment introduced substantial uncertainties into the overall risk characterization that were not quantified (Barnes 2010)

As underlined by the NG (2011) and Fisheries and Oceans Canada (2009) during the JRP process, methylmercury levels in Lake Melville biota had been impacted by prior hydroelectric development at Churchill Falls 300 kilometres upstream (Anderson 2011). This made the assertion that Muskrat Falls, only fifty kilometres upstream, would have no impact on Lake Melville highly questionable. However, it was difficult to use impacts from Churchill Falls to predict impacts from Muskrat Falls because peak impacts occurred in the early 1970s in the absence of systematic sampling efforts, and there was very limited available baseline data.

Potential human exposure impacts were estimated by combining future methylmercury levels in river fish (but not other local foods) with average intakes measured via a telephone survey and from previously published data (Golder Associates 2011). However, these analyses were poorly integrated and featured numerous modelling choices that underestimated risk. For example, Health Canada (2011) observed that Nalcor's use of community-average intake values in exposure calculations did not respect its advice to base risk calculations on higher intakes (e.g., 99th percentile). Health Canada further noted that even average intakes were likely underestimated because Nalcor had assumed anomalously small serving sizes and discarded higher intake values as "outliers" without apparent justification (Health Canada 2011). For example, in the underlying telephone survey data, only four households in North West River reported a value for maximum number of fish meals consumed in any one week, and one of these four values was discarded as an outlier (Minaskuat Inc. 2009).

In August 2011, the JRP issued its final report for Muskrat Falls (Government of Canada and Government of Newfoundland and Labrador 2011). Among the many recommendations were 1) full clearing of the reservoir; 2) "negotiations prior to impoundment" regarding indemnities for potential food consumption advisories that may impact Lake Melville resource users; and 3) the development of a pilot study between Natural Resources Canada, Nalcor Energy, and potentially other developers of hydro power to evaluate "the technical, economic and environmental feasibility of mitigating the production of methylmercury in reservoirs by removing vegetation and soils in the drawdown zone." The Government of Newfoundland and Labrador in its response agreed only to 1) partial clearing of trees in the reservoir; and 2) negotiations in the event that food consumption advisories are required (Government of Newfoundland and Labrador 2012). It referred the recommendation on the pilot study to Nalcor Energy. The Government of Canada declined to undertake the methylmercury-minimization study, noting that it "would be more appropriately led by a university-based research group," and directed the other two recommendations to the Government of Newfoundland and Labrador and Nalcor Energy (Government of Canada 2012). To our knowledge, Nalcor Energy did not publish a written reply to the JRP report.

3. An Interdisciplinary Research Program to Characterize Risks to Labrador Inuit

An ArcticNet research project, funded by the Canadian Government, "Lake Melville: Avativut, Kanuittailinnivut (Our Environment, Our Health)," elucidated the scientific uncertainties that had prevented a robust description of risks to Inuit health posed by the ongoing Muskrat Falls project (Durkalec, Sheldon, and Bell 2016a, b). This included a characterization of potential impacts on methylmercury concentrations in local foods webs and exposures to local Inuit. Prior to the completion of scientific research associated with this report, Nalcor was invited to participate in the Lake Melville research program by the NG but declined, asserting that there would be no impacts. Public statements by the Province and Nalcor have unwaveringly rejected the possibility that Muskrat Falls will have impacts on Lake Melville or human health (Fitzpatrick 2016; McKenzie-Sutter 2019; Roberts 2016).

3.1 Muskrat Falls and Mercury Cycling in the Lower Churchill River and Lake Melville

There have been major scientific uncertainties about the sensitivity of coastal waters and estuaries to changes in freshwater methylmercury inputs related to industrial development or climate change. The Churchill River accounts for roughly 70 per cent of freshwater inputs to Lake Melville, which features incomplete mixing between cold, saline sea water on the bottom and warmer fresh water near the surface where biological productivity is concentrated (Bobbitt and Akenhead 1982; Lu, DeYoung, and Banton 2014). However, the interaction between physical, chemical and biological processes had not previously been characterized, and there had been a complete lack of water and sediment mercury data.

A multi-year biogeochemical investigation of Lake Melville was conducted at Harvard University to measure mercury inputs to Lake Melville along with losses and transformations of key mercury species (including MeHg) in the water column, sediments, and biota (Schartup et al. 2015). A mass budget for methylmercury in the Lake Melville environment, which simulated physical processes (e.g., tidal and freshwater inputs, sediment cycling) and chemical transformations (e.g., Hg methylation), evaluated against data collected between 2012 and 2014, was then developed. This work demonstrated that local mercury methylation and inputs from the Churchill River interact with the strong stratification characteristic of many northern estuaries to promote bioaccumulation of methylmercury into the food web. This work established empirically the biogeochemical mechanisms by which perturbations in freshwater inputs (e.g., enhanced MeHg inputs from upstream hydroelectric development) may impact biota in the estuarine environment.

This mass budget for Lake Melville was expanded and nested within a broader probabilistic model to forecast the range of possible peak impacts of Muskrat Falls on environmental and biotic methylmercury levels in the Churchill River and Lake Melville (Calder et al. 2016). This in turn was integrated with a human exposures model described in Section 3.2. Local field data and reservoir design parameters were used to formulate these forecasts, which are subject to wide uncertainties that were represented in the estimates. The goal of this assessment was to identify the likely range of peak post-flooding impacts on water column and biotic methylmercury levels, which are typically realized within ten years (Bodaly et al. 2007; Schetagne and Verdon 1999; Schetagne and Therrien 2013). This analysis suggested a 90 per cent confidence interval for peak water column methylmercury of roughly 0.09 to 0.31 and 0.03 to 0.08 ng L^{-1} in the downstream river and estuarine surface, respectively, compared to a pre-impoundment seasonal average of roughly 0.02 ng L^{-1} in both. The final values suggested by Nalcor's analysis suggested a peak riverine methylmercury value of roughly 0.1 ng L^{-1} but did not include uncertainty characterization or allow for impacts on Lake Melville. The values forecasted using the Harvard model for the river environment were higher than, but consistent with, Nalcor's final analysis (Harris, Hutchinson, and Beals 2010) and similar to the values suggested by the screening analysis initially considered by the JRP (Government of Canada and Government of Newfoundland and Labrador 2011; Harris and Hutchinson 2008). The principal difference between the biophysical characterizations was the inclusion of Lake Melville in the Harvard modelling assessment.

3.2 Muskrat Falls and Mercury Risks to Lake Melville Inuit

To characterize the link between changes in environmental methylmercury and exposures among Labrador Inuit, the NG and Harvard researchers carried out a human health risk assessment. A dietary survey and methylmercury exposure assessment were completed in the winter, spring, and summer of 2014, in which 1,145 individuals from Inuit communities around Lake Melville participated. Participants reported their intake of local and store-bought foods, and a subset of volunteers (n = 571) provided hair samples, which were used to directly measure pre-flooding methylmercury exposures. Several hundred samples of local seafood were collected and analyzed for methylmercury. Research was conducted to identify whether the methylmercury in different country foods originated from freshwater or marine sources, and how much of each species lifespan was spent in different environments (Li et al. 2016). This allowed researchers to forecast the range of impacts that potential increases in methylmercury in the river and estuary would have on each species and hence on exposures among the Inuit population.

The potential range of peak increases in exposures among Lake Melville Inuit was estimated by substituting forecasted peak post-flooding methylmercury values into the baseline dietary assessment from 2014. On average across the population, peak methylmercury exposures were forecasted to be roughly double 2014 exposures if consumption patterns remained the same. This reflects the net contributions to individual diets of relatively highly impacted riverine species (e.g., brook trout) and primarily marine species with little to no expected impact (e.g., salmon). This, however, conceals substantial variability across the population with increases relative to 2014 levels ranging from no substantial increase to 450 per cent at the 95th percentile. The fraction of the population exceeding Health Canada's RfD following peak methylmercury concentrations associated with flooding was forested to increase from 1 per cent in 2014 to 5 per cent at peak exposures. These changes are most likely to occur within a decade of reservoir impoundment. At the 95th percentile in Rigolet, the most highly impacted community, exposures were expected to increase from roughly 0.4 $\mu g\ kg^{-1}\ day^{-1}$ in 2014 to 1.5 $\mu g\ kg^{-1}\ day^{-1}$ at peak (90% CI at this percentile: 0.6–2.3 $\mu g\ kg^{-1}\ day^{-1}$), compared to the U.S. EPA reference dose of 0.1 $\mu g\ kg^{-1}\ day^{-1}$ and Health Canada RfD of 0.2 (women of childbearing age and children) and 0.47 (everyone else) $\mu g\ kg^{-1}\ day^{-1}$ (Health Canada 2004; U.S. EPA 2000).

This analysis was the first prospective characterization of potential impacts on human exposure to methylmercury associated with hydroelectric flooding. Variability in exposure impacts was based on a list of traditional foods longer than what had previously been considered (i.e., including marine mammals) relevant for the Labrador Inuit. However, of this expanded list, only two species, representing less than 5 per cent of total methylmercury exposures, had mean expected peak increases higher than the range of increases considered by Nalcor's own human health risk assessment, which ranged from 127 to 500 per cent above pre-flooding values (Golder Associates 2011). The differences in interpretation for the significance to human health between the Harvard and Nalcor studies largely originated from consideration of the heterogeneity in exposures and intake of local foods among the Inuit population. Possible differences in risk across the population had been raised repeatedly and by many actors throughout the EIA process but was ultimately not considered quantitatively before the Harvard study (Government of Canada and Government of Newfoundland and Labrador 2011; Health Canada

2011). The results of Harvard's research were published in a peer-reviewed scientific journal in November 2016 but did "not provide evidence that would change Nalcor Energy's predictions" about impacts on Lake Melville Inuit (Sokal 2016).

3.4 Food Consumption Advisories: A Health-Protective Approach?

Elevated methylmercury levels in local foods are frequently managed with consumption advisories (Passos and Mergler 2008). In the context of Muskrat Falls, they have been the planned mitigation response since environmental assessments began (Minaskuat Inc. 2008). This was criticized by Natural Resources Canada (2009) and others as it shifted the burden of risk management onto impacted communities who have rates of food insecurity many times higher than the national average and depend on traditional foods for nutritional sufficiency (Organ et al. 2014; Rosol et al. 2011). Consumption advisories have caused unanticipated responses among Indigenous communities, including a loss of trust in traditional food systems (Furgal et al. 2005). Even advisories focused on certain fish species and targeted at vulnerable subpopulations have led to unexpected decreases in overall consumption (Shimshack et al. 2007). Generally, it is understood that consumption advisories must be deployed with due consideration of the countervailing benefits of existing diets and the nutritional profile of food replacement scenarios (Wheatley and Paradis 1996). The risk trade-offs of increased methylmercury exposure as compared to decreased nutritional sufficiency, have remained poorly characterized, and there has been little quantitative support for individual or policy decision-making.

Additional research at Harvard evaluated the impact of food consumption advisories on Lake Melville Inuit in comparison with potential risks from elevated methylmercury exposures resulting from Muskrat Falls (Calder et al. 2018). This work supplemented the results of the traditional food intake survey (Calder et al. 2016) with publicly available data on sales of store-bought foods (Government of Canada 2017), cross-referencing both with nutritional databases (Health Canada 2017; USDA 2017). Results showed that while traditional foods accounted for about 5 per cent of caloric intake on average across Lake

Melville Inuit, they represented roughly 70 per cent of n-3 fatty acid intake, 35 per cent of dietary vitamin D and a disproportionate share of many other nutrients. Nutritional data were cross-referenced with available confounder-adjusted dose-response relationships for cardiac, neurological, and cancer outcomes to estimate average population-wide net health impacts of diverse dietary scenarios (no change to diet, four scenarios that assumed replacement with store-bought alternatives, and a fifth that assumed replacement with local Atlantic salmon).

Results of the analysis suggested that, on average across the population of Lake Melville Inuit, replacement with store-bought foods would be associated with greater health impacts than increased methylmercury exposures assuming no dietary intervention. Replacement with Atlantic salmon improved outcomes. This demonstrated that the most health-protective intervention likely consists of promoting the most nutritious parts of the traditional Inuit diet (nutrient-rich, low-contaminant fish and seafood). This work provides a framework to inform decision-making around food consumption advisories, which is a controversial policy that tends to cleave between disciplines. For example, advisories have commonly been promoted by environmental scientists, while public health professionals have tended to be critical (Furgal, Powell, and Myers 2005; Wheatley and Paradis 1996).

4. The Independent Expert Advisory Committee

Results of the scientific research described above were published between 2015 and 2018. During this time, public pressure was mounting on Nalcor and the Government of Newfoundland and Labrador to give effect to the JRP recommendations, issued in 2011. In 2015, a JRP panelist publicly denounced the lack of action on and highlighted the risks of planned food consumption advisories (CBC News 2015). In 2016, a wave of hunger strikes, protests, and land occupations in Ottawa and Newfoundland and Labrador received substantial media coverage and led to criminal prosecutions against protesters and journalists (Breen 2017; Sokal 2016). Following these actions, the Government of Newfoundland agreed to convene an independent expert advisory committee following negotiations with the Labrador Inuit (NG), the Innu Nation, and the Labrador Métis

(NunatuKavut Community Council). The IEAC was mandated to "seek an independent, evidence-based approach [to] determine and recommend options for mitigating human health concerns related to methylmercury throughout the reservoir as well as in the Lake Melville ecosystem [using] best available science that incorporates Indigenous Traditional Knowledge" (Government of Newfoundland and Labrador 2016).

The IEAC comprised three Indigenous knowledge experts and six scientific experts (Nalcor consultants and government and academic researchers), reporting to a seven-member Oversight Committee, of whom four municipal and Indigenous representatives had voting power (Government of Newfoundland and Labrador 2017). One of the authors of this chapter (TB) was among the non-voting scientific experts. The IEAC was mandated (Government of Newfoundland and Labrador 2017):

- "to use the best available peer reviewed science and Indigenous knowledge [...] to assess and recommend options for mitigation of methylmercury impacts, including but not limited to [...] further clearing of the Muskrat Reservoir; and
- to review the plans for monitoring, monitoring results and key findings arising from research and monitoring, about or relevant for mitigation of methylmercury impacts; and
- to direct the research activities and recommend the design of new monitoring and mitigation measures for the protection of the health of Indigenous and local populations."

Specifically, the IEAC evaluated the benefits associated with (a) wetland capping and (b) targeted removal of soil in the Muskrat Falls reservoir area in order to reduce methylmercury production following impoundment. One of this chapter's authors (RC) served as a consultant to the IEAC, using the modelling tools described here to quantify the impact on exposures among Lake Melville Inuit of risk mitigation (Calder 2018).

Potential impacts on Inuit exposures under mitigation and no-mitigation scenarios were quantified using both the Harvard model (Calder et al. 2016) and the Nalcor model (Harris, Hutchinson, and Beals 2010). Nalcor had agreed to submit to the IEAC a scientific characterization of the interaction between Muskrat Falls and Lake

Melville to substantiate its assertions that there would be no impacts on Inuit health, but this report was never produced (Marshall 2018). Therefore, Nalcor's forecasts only described fish in the Churchill River but were substituted into the comprehensive framework from Calder et al. (2016) to evaluate implications for human exposure, inclusive of impacts on the downstream environment. The IEAC modelling outcomes suggested minimal benefits from wetland capping but that targeted soil removal may reduce the increase in MeHg exposures by roughly a quarter relative to the no-mitigation scenario (IEAC 2018). Despite using a completely different methodology, the values proposed by Harris et al. (2010) for the river environment fell within the reported confidence interval of Calder et al. (2016) (IEAC 2018).

After this analysis had been completed, the IEAC received a submission from a separate Nalcor consultant claiming that forecasted impacts on Churchill River and Lake Melville biota violated the principles of conservation of mass (Azimuth Consulting Group Partnership 2018). The IEAC noted that this document contradicted not only Calder et al. (2016) but also Harris, Hutchinson, and Beals (2010), which had served as Nalcor's official characterization of the methylmercury risks associated with Muskrat Falls for nearly a decade (IEAC 2018). The submission of contradictory impact assessments created substantial confusion within the IEAC about what Nalcor was claiming would be the impacts of Muskrat Falls on environmental methylmercury levels (Kirk 2018).

Ultimately, three of the four voting members of the IEAC Oversight Committee voted for both wetland capping and soil removal, while the Innu Nation voted for wetland capping only. Non-voting members of the Oversight Committee (representing government and Nalcor) opposed mitigation (IEAC 2018). The IEAC also recommended continued environmental monitoring (full consensus) and an impact security fund to pay indemnities in the event of identified impacts (consensus of voting members only) (IEAC 2018). These votes were based on the observation that all available scientific information suggested an appreciable, if uncertain, impact of Muskrat Falls on methylmercury levels in local wildlife and human exposures. For example, the mayor of North West River, representing impacted municipalities, commented that considering the work of "[Harris, Hutchinson, and Beals (2010)] and [Calder et al. (2016)], using the best information available, similar outputs were forecasted, and both predict significant increases" (Kieser 2018).

The Government of Newfoundland and Labrador declined to act on the mitigation recommendation of the IEAC. The Province held the decision in "review" until announcing that the deadline had been "unintentionally missed" (Careen 2018; Maher 2019). At all times, Nalcor Energy and the Government of Newfoundland and Labrador claimed that there was no possibility for impacts on Lake Melville or the health of the Lake Melville Inuit. In the summer of 2019, however, the Commission of Inquiry Respecting the Muskrat Falls Project, convened to study broader controversies surrounding Muskrat Falls, published Nalcor's belated analysis of potential impacts on Lake Melville. It concluded that peak methylmercury levels in Lake Melville may range from 30 to 110 per cent beyond baseline (Baird 2018) as compared to an expected peak of 160 per cent (90% CI: 60–310%) beyond baseline in Calder et al. (2016). Crucially, that analysis for Lake Melville considered as inputs the river impacts considered by Nalcor (Harris et al. 2010), which were less than those suggested by the authors, and did not include local production of methylmercury in Lake Melville identified in Schartup et al. (2015) and included in the original Harvard model forecasts (Calder et al. 2016). After adjusting for different assumptions about impacts on the river environment, the internal analysis by Nalcor suggests that the impact of river methylmercury on estuary methylmercury is even larger than the analysis presented by Calder et al. (2016) and Schartup et al. (2015) which Nalcor had spent years trying to discredit.

By October 2019, the Muskrat Falls reservoir was fully flooded. All stakeholders are waiting for data to become available on the impact on aquatic and biotic methylmercury levels. Peak methylmercury levels are likely to be observed in the aquatic environment in the first one to five years and in biota in the first two to ten years. No action was taken to attenuate potential impacts despite the recommendations of the IEAC in 2018 or the similar recommendations of the JRP in 2011 (Government of Canada and Government of Newfoundland and Labrador 2011). Methylmercury levels are rising but have not yet stabilized (NL MAE 2019). For example, average September 2019 dissolved methylmercury levels at the outfall of the Churchill River were 50 per cent greater than those in August 2019, when flooding was completed. For comparison, in previous years, dissolved methylmercury had decreased by 7 per cent (2018) and 18 per cent (2017) from August to September. Average methylmercury levels at the outfall in September 2019 were therefore more than double those in September 2018. The current reported detection limit (0.01 ng L^{-1}) should be adequate to resolve impacts on the aquatic environment as it is roughly half of seasonal average values for pre-flooding methylmercury levels (Schartup et al. 2015).

5. The Future of Canadian Hydro Power

The conflict between Canadian hydroelectric development and Indigenous welfare and sovereignty is not going away. In 2016, all twenty-two hydroelectric projects then under development or evaluation across Canada projects then under consideration or construction were within 100 kilometres of Indigenous population centres, of which eighteen projects representing 90 per cent of capacity were likely to have some methylmercury impact (Calder et al. 2016). Indigenous Peoples are increasingly asserting their legal right to consultation and consent regarding projects that are likely to impact their traditional lands, their food systems, and their health. However, Muskrat Falls has demonstrated that numerous scientific and institutional barriers prevent proactive management of these risks. Promoters of hydroelectric projects continue to rely on reactive mitigation measures such as food consumption advisories rather than proactive management such as environmentally informed site selection and design (Warner and Coppinger 1999).

The research program developed to investigate potential risks associated with exposure to methylmercury following flooding of the Muskrat Falls facility developed tools to better understand a dynamic socio-environmental system. Methylmercury risks are only part of a longer list of impacts of hydroelectric projects, which disrupt terrestrial as well as aquatic food systems and affect water supply, biodiversity, and a number of other ecological endpoints of interest (Rosenberg et al. 1997). Hydroelectric development transforms ecosystems, resulting in new biological, chemical, and physical equilibria as a function of site-specific, interacting phenomena for which there is a lack of prospective modelling capacity.

Institutional mechanisms to promote integration of the latest science with risk forecasting, mitigation, and management are needed. For example, citing federal guidance from 1987, Manitoba Hydro considers methylmercury risks associated with a threshold almost thirty times greater than the U.S. EPA RfD (Manitoba Hydro 2014). Such gaps will lead to conflict with Indigenous groups who are increasingly representing their interests with scientific characterizations larger in scope and using more recent methods than the assessments required of project developers (Durkalec, Sheldon, and Bell 2016a). In the case of Muskrat Falls, federal scientists served as impartial referees of available evidence and provided crucial commentary on the gaps in the environmental assessments (Government of Canada and Government of Newfoundland and Labrador 2011; Health Canada 2011; IEAC 2018; Natural Resources Canada 2009). Ultimately, however, there was no legally binding mechanism requiring the developer or the Province to enact their advice.

Traditionally, scientific advice underpinning Canadian political decisions has been characterized by secrecy and extremely limited possibility for external challenge (Leiss 2000). In environmental assessments, this problem is compounded by a large provincial jurisdiction and a closeness between provincial governments and project developers that impairs objectivity (Fitzpatrick and Sinclair 2009). Many development projects are carried out by government-owned Crown corporations, which have wide latitude to define the scope, scale, and methods of environmental, social, and human health impact assessments, creating a situation likened to "the fox guarding the henhouse" (Warner and Coppinger 1999). In the case of Muskrat Falls, the "close relationship" between regulator and developer has had serious adverse impacts on the effectiveness of government oversight, in environment and in other areas (Doelle 2012)

A policy model where environmental decisions are informed by transparent and independent science is still evolving in Canada (Leiss 2000). This progress is extremely uneven across Canada, as provinces have different approaches to implementing federal guidance which is viewed as more impartial but is largely nonbinding (Fitzpatrick and Sinclair 2009) and in valuing the benefits of human health protections (Calder and Schmitt 2015). For example, the Province of Quebec reacted to confrontations with Indigenous populations in the 1960s and 1970s by creating institutions such as the Bureau d'audiences publiques and promoting project-specific committees with both Indigenous rightsholders and scientific experts (Filiatrault 2007). Such institutions aim to build consensus between Indigenous stakeholders and government in the development of natural resource projects and to increase public confidence in scientific assessments underpinning environmental decisions. Mechanisms that increase the impartiality and transparency of environmental risk assessments and the scientific basis for decision-making are needed more broadly.

Endnotes

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5 The term "Muskrat Falls" is here used to describe the hydroelectric project on the lower Churchill River at Muskrat Falls. It is the cornerstone of the broader Lower Churchill Project conceived to transmit hydro power from Labrador to Newfoundland, the Maritime provinces, and New England.

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