Lake Melville:

Avativut, Kanuittailinnivut
(Our Environment, Our Health)

SCIENTIFIC REPORT

Nunatsiavut Government

2016

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A calm night aboard the M/V *What's Happening* during the Lake Melville field campaign.

Credit: Rodd Laing

PREFACE

Lake Melville is an ecologically and culturally significant subarctic estuary located mostly within Labrador Inuit territory. It is central to Inuit subsistence and well-being and has supported a thriving Inuit society for centuries. Nalcor Energy, the provincial energy corporation of the Government of Newfoundland and Labrador, is currently developing the first phase of the Lower Churchill hydroelectric project – the Muskrat Falls dam and reservoir – upstream from Lake Melville. During the project environmental assessment and subsequent approvals by federal and provincial governments, however, little was known about potential downstream impacts on Lake Melville and the surrounding Inuit population. The environmental assessment panel concluded that this knowledge gap was compounded by Nalcor's decision to exclude Lake Melville from the environmental assessment and from detailed study. Nalcor based its decision on their prediction that there would be no measurable impacts downstream.

The Lake Melville: *Avativut, Kanuittailinnivut* research program was initiated by the Nunatsiavut Government, the Labrador Inuit self-government body, to fill this knowledge gap. Independent research by a team of expert scientists from Canada and the United States carried out extensive field programs and data synthesis using state-of-the-art research methods to develop an authoritative understanding of key processes and dynamics in the estuary. The primary research objective was to understand how Muskrat Falls would impact the Lake Melville ecosystem and Inuit who depend on it for their well-being. A secondary objective was to anticipate the potentially compounding impacts of changing climate. These findings create a robust baseline understanding of the Lake Melville ecosystem and potential future changes, particularly with regards to two main areas of concern for human health: 1) methylmercury in country food and 2) ice and ice-based travel. The project was co-led by Tom Sheldon, Director of the Environment Division at the Nunatsiavut Government and Trevor Bell, Professor of Geography at Memorial University of Newfoundland.

Some of the results presented have already been published in the peer-reviewed scientific literature or are in the process of being published, including in highly respected international journals. The results reported here provide the scientific foundation for the Lake Melville: *Avativut, Kanuittailinnivut* Policymakers and Community reports.


Field work for the Lake Melville research program.

Credit: Rodd Laing

SUMMARY OF KEY FINDINGS:

Understanding The System And Expected Future Changes To Lake Melville

This report presents findings regarding key processes and dynamics in the Lake Melville estuary from the Lake Melville: *Avativut, Kanuittailinnivut* research program related to five themes: methylmercury; sediments and organic carbon; physical lake processes; climate; and ice monitoring. Detailed methods and findings on each theme are reported in the chapters that form the body of this report. Below, key findings on each theme are reported. Findings encompass new knowledge regarding current and historical processes and dynamics in the estuary to create a comprehensive baseline understanding of the Lake Melville ecosystem. They also predict and project future changes related to the Muskrat Falls hydro project and potentially compounding effects of climate change.

Methylmercury

- Presently, rivers are a major source of mercury to Lake Melville; they provide more than 85% of the total mercury input. Strong water column stratification results in a low salinity surface layer enriched in mercury that extends across Lake Melville from Churchill River to Groswater Bay.

- Inorganic mercury can be converted to methylmercury under the right conditions. Methylmercury is the only form of mercury that biomagnifies in the food web and is associated with negative effects on the developing brain and cardiovascular health in adults. Presently, the main source of methylmercury in Lake Melville is production in the upper water column (surface waters) and the second largest source is inputs from rivers.

- Stratification of Lake Melville results in a concentration of biological activity in surface waters. This concentrated biological activity facilitates conversion of inorganic mercury into methylmercury, enhancing uptake into the base of the food web (plankton). This is one reason that bioaccumulation of methylmercury in Lake Melville is very efficient.

- In the future, methylmercury inputs from the Churchill River are likely to become the largest source to Lake Melville. Experimentally flooded soils from the future Muskrat Falls reservoir area showed a spike in methylmercury concentrations within 72 hours, and a 14-fold increase in methylmercury concentrations within 120 hours, at which point levels were still increasing but monitoring ended. Organic material provides food for bacteria responsible for converting inorganic mercury in the ecosystem to methylmercury, so the actual pulse is likely to be much greater. Elevated levels of methylmercury are anticipated to last for several decades.

- Stable year-round stratification and the concentration of biological activity in the surface waters of Lake Melville means that increased methylmercury inputs from the Churchill River after flooding are likely to be efficiently taken up in the food web.

- Measured hair mercury (Hg) levels (a reliable measure of methylmercury levels) indicate that methylmercury exposures of Inuit in the Lake Melville region are higher than those of the general Canadian population. Half of the hair samples from Inuit residing in the Lake Melville region were above 0.38 µg Hg/g in June and 0.51 µg Hg/g in September and the highest five of every 100 samples in September averaged 2.45 µg Hg/g. For the general population in Canada, prior work shows half of the samples are above 0.20 µg Hg/g and the top five out of every hundred average 1.18 µg Hg/g.

- In general, methylmercury exposures were higher in Rigolet and North West River than in Happy Valley-Goose Bay. Methylmercury exposures were generally higher among men than among women and children. Survey participants in Rigolet reported consuming more seal liver and meat compared to those in Happy Valley-Goose Bay and, in general, men consumed a greater quantity of locally harvested foods than women and children.

- Concentrations of mercury in less than 10% of Inuit hair samples exceeded the level corresponding to Health Canada's reference dose for women of childbearing age and children (approximately 2 µg Hg/g hair). No women of childbearing age (16–49) or children were found to exceed this exposure level.

- Locally harvested salmon and cod account for the largest fractions of Inuit methylmercury exposures. Cumulatively, locally harvested foods account for between 51% (March) and 67% (June and September) of total methylmercury exposures, with the remaining fraction from store-bought fish and shellfish.

- Modelling of methylmercury exposures under post-impoundment conditions reveals that the number of Inuit potentially pushed above the Health Canada guideline for methylmercury exposure ranges from 32 individuals under the low methylmercury scenario if the reservoir is completely cleared, including topsoil, to over 200 individuals under the high scenario.

- Even under the low methylmercury scenario, which requires complete removal of topsoil, vegetation and trees, and rapid decomposition of methylmercury in downstream environment, there will be an overall increase in methylmercury exposures.

- Under the high methylmercury scenario, there may be some individuals who consume greater amounts of country foods whose methylmercury exposures can increase by up to 1500%.

- Rigolet residents are at higher risk of increased mercury exposures due to flooding because of their greater reliance on locally caught food, with up to 46% of the community exceeding the most conservative Health Canada reference dose and up to 66% exceeding the U.S. EPA reference dose under the high scenario.

Sediments and organic carbon

- Sediments contribute an important component to northern ecosystems by providing a habitat for biota (benthos), a repository for organic and inorganic substances entering or produced within the ocean, a reactor and source of transformed substances back to the water column, and a mechanism of burial (e.g. for contaminants). Sediments interact with ice, ocean and the surrounding land over a wide range of space and time scales so they also preserve a record of ecosystem properties.

- The Churchill River is the main source of sediment to the Lake Melville system. Although some of this sediment is trapped in Goose Bay, the majority is transported eastward into Lake Melville proper and supports high sedimentation rates in a series of troughs and basins to the east of Goose Bay Narrows. Perturbations to the sediment supply from the Churchill River due to climate change or Muskrat Falls will likely impact overall sedimentation and the potential for burial of carbon and contaminants throughout Lake Melville.

- The Churchill River is also the main source of terrestrial organic carbon to the Lake Melville system at the present time. Because conditions for primary production are relatively poor throughout much of the lake system (low surface water clarity, short surface water residence time), it is likely that terrestrial organic carbon is an important source of metabolic energy. Because of this, changes in the supply of terrestrial organic matter from the Churchill River to Lake Melville could impact the metabolic energy in the system, with implications for planktonic and benthic bacterial communities.

- Results suggest that the Churchill River plume is a principal mechanism for transporting land-derived sediment and organic matter eastward through Goose Bay Narrows into Lake Melville. A small seasonal shift in the discharge of the Churchill River from reservoir development (e.g. slight flattening of the hydrograph) may decrease the extent of this plume or alter its timing, impacting the distribution of terrestrial sediment and carbon and thus possibly food web structure in Lake Melville.

- Evidence points to enhanced marine primary production in the eastern end of Lake Melville, compared to the west. This trend is consistent with the increasing surface water clarity eastward (beyond the turbid plume of the Churchill River), and the notion that the Rigolet Narrows are an upwelling area, which replenishes nutrients in surface waters. Additional data are needed to confirm and understand the magnitude and controls on marine primary production in this system. However, because the Churchill River plume affects light penetration in the water column, changes in the plume extent or character may be expected to impact at least some aspects of marine primary production in Lake Melville.

- The sedimentary record indicates that the supply of terrestrial organic matter to Lake Melville has increased in recent decades. Increased supply could be associated with altered quantities or timing of river runoff (which impacts transport of materials in the plume), enhanced release of sediment and organic carbon from reservoir flooding, and/or increased streambank erosion due to thawing of permafrost, vegetation changes, or forest fire activity. The greatest change is observed in central Lake Melville, which suggests that this area is responsive to changes in rivers and/or their watersheds, despite being quite removed from the actual river mouths. Future changes in the supply of terrestrial organic matter associated with Muskrat Falls or climate change and variability are likely to be recorded in the sediments throughout Lake Melville.

- Simple calculations show that inputs of sediment and terrestrial organic matter to Lake Melville could increase by nearly double following flooding of the Muskrat Falls reservoir. Based on previously impounded systems this increased input is expected to decrease once the shoreline readjusts to the new water level, but the timeline for readjustment is unknown and could be on the order of decades.

Physical lake processes

- Three key physical processes influence Lake Melville dynamics:

  1. The exchange of saltwater and freshwater between Lake Melville and the coastal Labrador Sea over a shallow sill at the Rigolet Narrows, which has major significance for the physical and biochemical characteristics, transport, and renewal of Lake Melville waters.

  2. Tides, which account for about 55% of the variance of the currents below the surface layer and extend down surprisingly deep into the lake. The flow near the sill is very energetic with variability dominated by tidal influences. Tidal flows diminish in importance away from the Narrows at Rigolet and become negligible at the head of the lake. The long-term mean flow is also strongly influenced by the freshwater input from rivers. Wind-forcing plays a significant role in the dynamics over the main body of the lake, particularly in the late fall and early winter, when there are strong wind events and the lake is not covered in ice.

  3. Freshwater discharged at the mouth of the rivers, primarily the Churchill and Northwest Rivers, and its movement across Lake Melville. River discharge is a major driver of the lake's estuarine circulation. Variations in its intensity or seasonal cycle impact the lake's temperature and salinity distribution and processes of ice formation.

- Stratification in the lake is very strong in the upper part of the water column year-round. During the part of the year when lake is ice covered, ice decouples currents from the wind field and limits the surface tidal response inside the lake. These effects mean that the lake is much 'quieter' in the winter with weaker currents and even less mixing of water than in summer, both in the lake and at the sill at the Rigolet Narrows.

- The residence time of water increases with depth, with surface water exchanging relatively quickly and deep water exchanging irregularly. The flushing time of the lake is estimated to be 192 days.

Seal hole and snowmobile track at Double Mer

- The Upper Churchill hydroelectric development did not significantly change the annual mean volume of river discharge, but observations demonstrate that it has a strong impact on seasonal variations in Churchill River discharge.

- Model simulations demonstrate that freshwater discharge has the strongest influence on the seasonal variations of water characteristics in the vicinity of the mouth of Churchill River where freshwater discharges into Goose Bay. This area is also where the greatest change in the ice thickness and ice concentrations occurs in the lake before and after the Upper Churchill development, according to model simulations.

- Our work provides an oceanographic baseline upon which to conduct further long-term monitoring of the Lake Melville environment. It identifies: 1) the most important regions for monitoring physical characteristics of the lake response to any variations in freshwater discharge; and 2) the physical characteristics that are most sensitive to these variations.

- Changes in the amount and seasonal timing of freshwater inflow, for example associated with Muskrat Falls, can potentially influence the formation of ice in the lake, the mixing of water in the lake and over the sill, and the residence time of water in the lake, but the significance of these changes and any implications on the timing, duration, and extent of ice cover and ice-based travel on the lake by local residents remains unknown and should be investigated in future work.

Climate

- Climate in Labrador is gradually warming; however, over the past half century this change remains small relative to the pronounced natural variability the region experiences. This includes slow (10 to 30 year) climate cycles associated with the North Atlantic Oscillation (NAO; shifts in atmospheric circulation) and Atlantic Multidecadal Oscillation (AMO; shifts in sea surface temperatures).
- Labrador has undergone a number of climate regime shifts in the past 60 years, which are largely explained by fluctuations in the preferred state of the NAO and AMO. These include a neutral period from the 1950s through 1979, a cold period from 1980 to 1997, and a warm period from 1998 onwards.
- Recent extreme climate events (e.g. winter warmings of 2009/10 and 2010/11) affecting Labrador are strongly connected to these climate fluctuations, particularly the NAO. Ongoing climate change is expected to increase the likelihood of similar extreme warmings in the future, although they will remain more likely under favourable phases of the NAO and AMO.
- Lake Melville ice climatology shows a significant relationship with regional and local climate, with later freeze-up and earlier break-up connected to warm temperatures in fall and winter respectively. Available ice data is too limited to confidently establish connections between ice climatology and Churchill River discharge.
- Hazards related to warm climate anomalies are expected to be a significant issue for some time, as Labrador may remain in a warm climate regime for years to decades. At some point, a return to a cooler-than-normal climate regime may again obscure the impacts of ongoing global climate change; any such shift will be temporary.
- Ongoing climate change is expected to increase the occurrence of warm anomalies into the future, even as the current warm regime comes to an end. This is likely to impact ice use and safety.

Ice monitoring

- Changes to the ice regime in Lake Melville driven by environmental changes can have serious consequences for the health and well-being of Inuit. Safe, stable ice is critically important for accessing country food resources and travel between communities. Increased unpredictability and variability in ice and weather conditions and decreases in ice cover, strength, and stability are increasing physical health risks for ice users.
- Community-based and real-time monitoring of ice and snow conditions in the Lake Melville area are essential to enhance information available to Inuit regarding current conditions to help manage increasing ice-based travel risks.
- Prototype *SmartICE* (Sea-ice Monitoring And Real-Time Information for Coastal Environments) ice thickness buoys and sensors are able to provide daily ice and snow thickness information based on detailed temperature data.
- Community-based monitoring results demonstrate significant annual variation in ice thickness and snow depth in Lake Melville, which may be related to a number of environmental and climatic factors.
- Integration of local and traditional knowledge about ice conditions with *in situ* ice monitoring devices and technology provides a better and more comprehensive understanding of the ice regime on Lake Melville and surrounding areas.
- Communication of snow and ice monitoring information in an accessible format is imperative for ensuring this information can be received and understood by end users. Therefore, a user-friendly, community-level online information portal is being developed that integrates all the information from community-based monitoring stations, real-time ice, snow and water sensors, satellite images and Canadian Ice Service ice-charts in one location.

Rigolet.

Credit: Build Films

1. INTRODUCTION

Agata Durkalec

1. 1. Overview and report organization

Estuaries are among the most biologically productive habitats in the world. Many coastal Arctic and subarctic estuarine regions are experiencing the dual stressors of industry-related activities and climate change. However, our understanding of these complex systems – how they are responding to external pressures and implications for the health and well-being of northern communities – is inadequate. This report presents findings from a large research program that investigated the ecosystem status and current and potential future influences of hydroelectric development and climate change on Lake Melville, a large subarctic estuary in northern Canada on which Inuit rely for subsistence harvesting.

Lake Melville is a large an estuary that is part of Hamilton Inlet, a coastal inlet that stretches 250 km and is the largest single body of water in Labrador (Fitzhugh, 1972). Lake Melville is about 2,100 km^2 and includes a small shallow bay called Goose Bay that extends off the main basin on the western end of the lake. On the eastern end of the lake, a constricted strait called the Narrows (referred to throughout as the Rigolet Narrows) separates Lake Melville from Groswater Bay and the Atlantic Ocean. There are four major rivers that discharge into Lake Melville: the Northwest River, Kenamu River, Goose River, and Churchill River. Of these, the Churchill River is by far the largest freshwater source to Lake Melville. It is also Labrador's largest river, draining a watershed of approximately 120,000 km^2 (Anderson, 2011). These rivers add sediment-enriched freshwater to the cold saltwater derived from the Atlantic Ocean. This creates a dynamic environment that supports notably high productivity and species diversity, and has resulted in Lake Melville being identified as Ecologically and Biologically Significant Area by the Canadian Science Advisory Secretariat (2013). This diversity includes freshwater fish species such as lake whitefish, longnose and white suckers and diadromous fish species that live in the ocean and return to Lake Melville to feed, such as brook trout and rainbow smelt. Atlantic salmon and sea run brook trout have several spawning and juvenile rearing areas in the lake and its tributaries. The lake supports the largest concentrations of surf scoter, a large sea duck, in eastern Canada; is an important ringed seal overwintering and breeding area and harbour seal habitat; and is a feeding area for marine mammals such as dolphins, humpback whales, minke whales, and harp seals.

Lake Melville is part of the Labrador Inuit homeland. It is tremendously important to Inuit, who have depended on it for centuries for subsistence hunting and fishing (Brice-Bennett, 1977). Harvesting, sharing, and consumption of foods derived from the land – country foods – are critical for Inuit health, well-being, and culture. Ice cover on the lake for nearly half of the year facilitates travel for Inuit to neighbouring communities and harvesting areas, and the activity of travel on ice is itself culturally important.

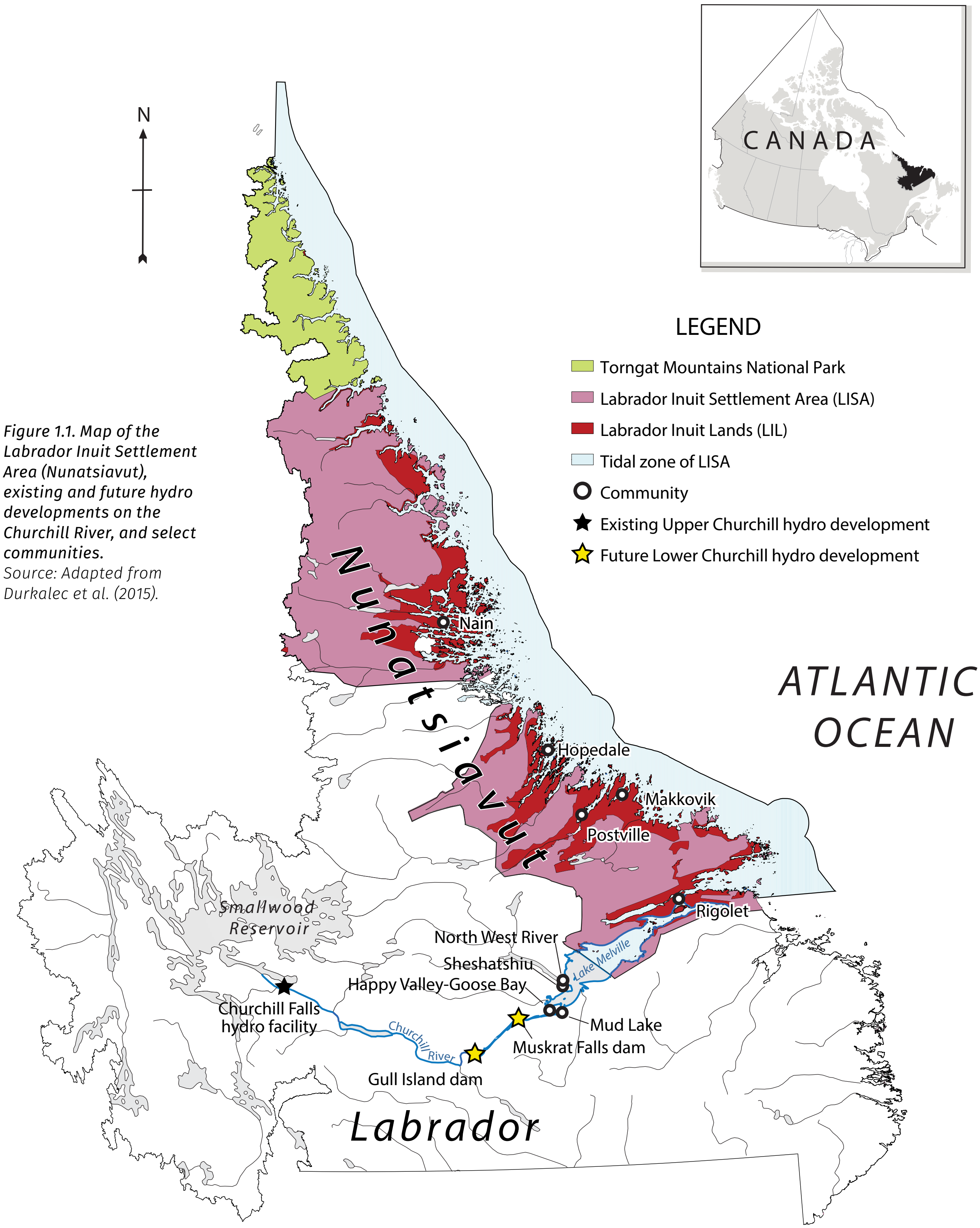


Figure 1.1. Map of the Labrador Inuit Settlement Area (Nunatsiavut), existing and future hydro developments on the Churchill River, and select communities.
Source: Adapted from Durkalec et al. (2015).

Labrador Inuit have a settled land claim with the provincial and federal governments that covers much of northern Labrador, and includes most of Lake Melville (Figure 1.1). Thousands of Inuit live on the shores of Lake Melville in four communities in and outside of the land claim area, in addition to thousands of non-Inuit residents.

There is evidence that climate change and impacts of an existing hydroelectric development on the Churchill River, called Churchill Falls or the Upper Churchill hydroelectric development, have and are continuing to alter the Lake Melville environment (Anderson, 2011; Cunsolo Willox et al., 2012; Nickels et al., 2006). Additional impacts are expected from a new large-scale hydroelectric development called the Lower Churchill project, which includes two large dams on the Churchill River at Muskrat Falls and Gull Island. Construction of the Muskrat Falls dam is currently underway.

It is well established in the scientific literature that during reservoir creation, the inundation of terrestrial lands with water stimulates bacteria to convert inorganic mercury to biologically active methylmercury (Hall et al., 2005, 2004; St Louis et al., 2004, 2001). Methylmercury is a potent neurotoxin that bioaccumulates in food webs. It can cause brain impairment in infants and children and cardiovascular problems in adults (Health Canada, 2011; Karagas et al,. 2012). Methylmercury contamination in the marine food web is a serious concern for Inuit who rely on country food for their sustenance and well-being.

Nalcor Energy, the Newfoundland and Labrador provincial energy utility and project proponent, predicted that there would be “no measurable effects” downstream on Lake Melville from the Lower Churchill project and thus excluded Lake Melville from the environmental assessment (EA) area (Nalcor Energy, 2011, 2009a). Consequently, Nalcor did not carry out detailed study and rigorous assessment of the potential impacts of the proposed development on Lake Melville.

The independent joint federal-provincial EA panel for the Lower Churchill project (“the Panel”) found Nalcor’s claims regarding downstream impacts unsubstantiated and recommended a new comprehensive downstream impacts assessment (Joint Review Panel, 2011). Federal and provincial governments approved the project without the full implementation of the Panel’s recommendation, and despite high uncertainty about potential impacts.

From the beginning of the EA for the Lower Churchill project, the Nunatsiavut Government has been of the view that objective, transparent, and credible science is needed to support good decision making, as Inuit health, culture, and rights are at stake. As a result, the Nunatsiavut Government spearheaded a research program to gather objective baseline knowledge about this important estuary to inform predictions of future impacts and changes prior to reservoir flooding and create the basis for a monitoring plan that is credible and protective of Inuit health. This report is the culmination this work.

The report is organized into four main sections. Chapter 1 provides an overview of the regional context and describes existing and future hydroelectric developments in the Lake Melville watershed. An overview of the EA process for the Lower Churchill project is presented, including the key knowledge gaps that became the impetus for this research program. Chapters 2 to 6 present baseline knowledge about how the Lake Melville system functions related to key areas of investigation, including physical lake processes, climate influences, ice, sediment and organic carbon cycling, and methylmercury production and current human exposure to methylmercury. They also present future predictions of changes in Lake Melville and impacts of those changes on the ecosystem and human health.

1. 2. Regional setting: Nunatsiavut, the Labrador Inuit homeland

> *Nunatsiavut is the homeland of the Labrador Inuit. This homeland includes the land, sky, water and the ocean. Nunatsiavut has enabled its ancestors to thrive as self-reliant, self-sufficient people. It has defined their culture, their skills and their strengths as a people. It has sustained the Labrador Inuit through a long history of change brought about by colonialism, resettlement and dislocation from their traditions. It has become the solid base from which they can protect their cultural foundation and reclaim control over their economic and political destiny through self-government.*
>
> (Nunatsiavut Government, 2011a)

Northern Labrador is the traditional homeland of Labrador Inuit, who have lived and thrived in this region in close relationship with the natural environment for millennia (Brice-Bennett, 1977). The political autonomy of Labrador Inuit and their Aboriginal harvesting rights within their traditional lands are recognized through the Labrador Inuit Land Claims Agreement (LILCA), a treaty with the Government of Canada and provincial government of Newfoundland and Labrador. Based on a land claim filed in 1977, the settlement of LILCA resulted in the formation of the Nunatsiavut Government in 2005, the first Inuit self-government body in Canada.

LILCA defines the Labrador Inuit Settlement Area (LISA) of Nunatsiavut, meaning "Our Beautiful Land" in Inuttitut. LISA covers 72,520 km^2 of lands and waters and 48,690 km^2 of sea to which Labrador Inuit have special rights including subsistence harvesting rights. Of these lands, Inuit own 15,800 km^2, termed Labrador Inuit Lands (LIL). LISA covers a vast territory in northern Labrador and extends south to Lake Melville, where it encompasses the central and eastern parts of the lake and surrounding lands. In addition, through a provision in LILCA (Schedule 12-E), Inuit have special subsistence harvesting rights outside of LISA around the lands and waters in the most western extent of Lake Melville.

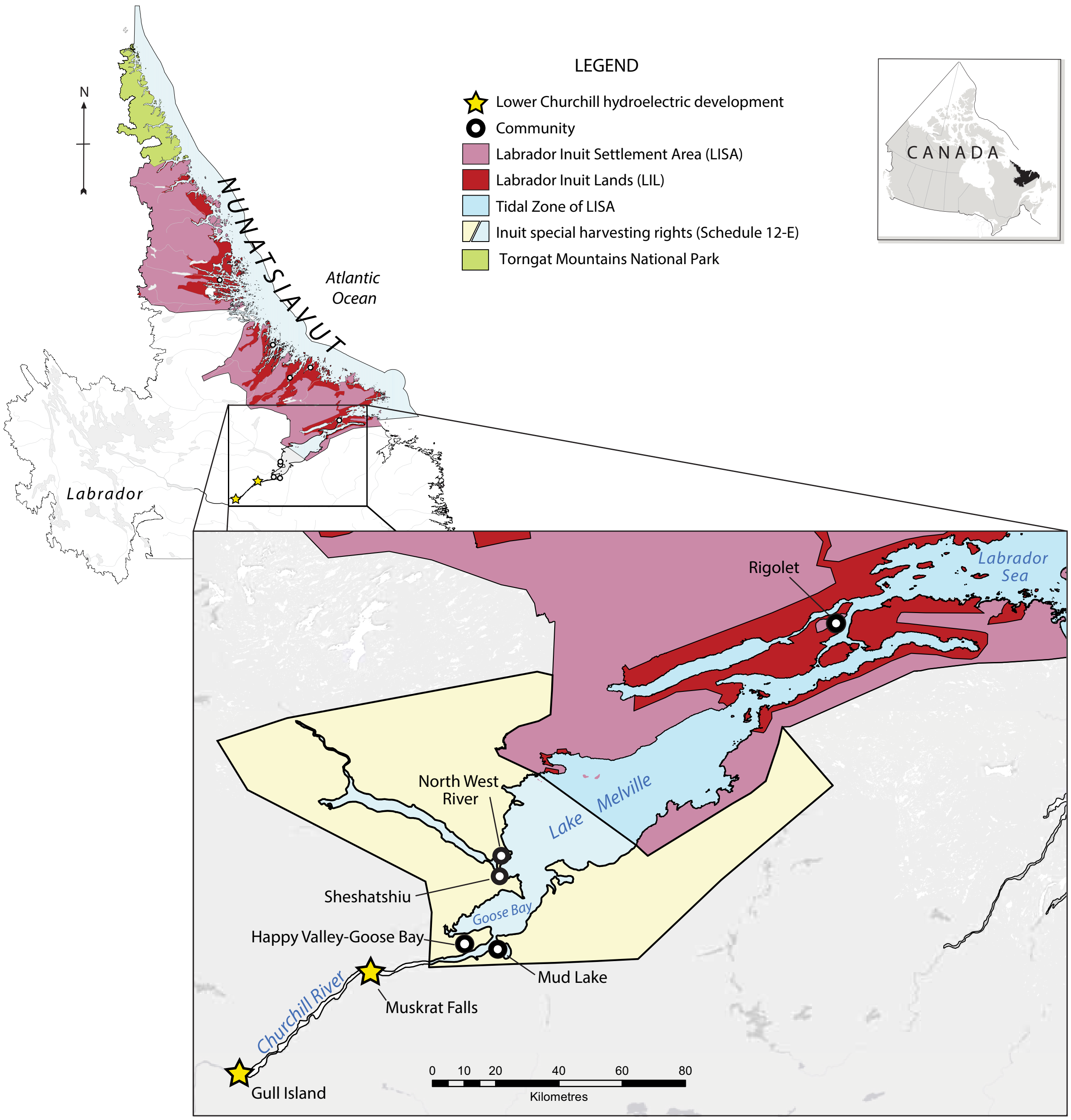


Figure 1.2. Close up of the Churchill River and Lake Melville showing surrounding communities and the boundaries of the Labrador Inuit Settlement Area.

Table 1.1. Total and Inuit populations in the greater Lake Melville area

Lake Melville Community	Total population[a]	Inuit population[b]	% Inuit
Within Nunatsiavut			
Rigolet	306	260	85%
Outside Nunatsiavut			
North West River	553	290	52%
Sheshatshiu First Nation	1,314	20	2%
Mud Lake	54	40	74%
Happy Valley-Goose Bay	7,552	1,925	25%
Total	**9,779**	**2,535**	**26%**

[a]*Statistics Canada (2012)*

[b]*Statistics Canada (2013)*

The total population of Nunatsiavut is 2,617, of which 2,325 or 89% are Inuit (Statistics Canada, 2014). Five Inuit communities are located within the boundaries of Nunatsiavut. Rigolet is the most southern of the five communities and is located on the eastern end of Lake Melville, near the Rigolet Narrows. The Nunatsiavut Government also represents Inuit living outside of the boundaries of Nunatsiavut, including Inuit living in the Upper Lake Melville communities of North West River, Mud Lake, and Happy Valley-Goose Bay (Table 1.1). Sheshatshiu is a First Nations reserve located close to North West River with a primarily Innu population, although a small number of Inuit also report residing there.

1. 3. Lake Melville is our home: Inuit land use and connections to the land

The land keeps us healthy – the land, the sea, and the ice keeps us healthy, and it's who we are.

–Rigolet resident (Nunatsiavut Government, 2011b)

Labrador Inuit have a close relationship with the environment based on ongoing connections to and dependence on traditional lands, and a worldview that places significance on the unity of humans and the natural world (Brice-Bennett, 1977; Durkalec et al., 2015; NAHO, 2011; Pufall et al., 2011).

Harvesting and consumption of country food

Country food, or wild foods such as marine mammals, fish, terrestrial game, and plants that are harvested from the land and sea, are important for Inuit health and well-being. Ninety percent of Nunatsiavut residents over 15 years of age reported harvesting country food in the prior 12 months (Wallace, 2014). Food sharing networks are strong in Nunatsiavut, with a majority of households reporting that family and friends share country food with them (Egeland, 2010). Country food is rich in antioxidants, omega-3 fatty acids, monounsaturated fatty acids, protein, and micronutrients (CINE, 2015). As such, it makes a critical nutritional contribution to diets in a region with high market food costs and nearly five times the level of moderate to severe food insecurity as the general Canadian population (Egeland, 2010). Harvesting itself is associated with physical, cultural, material, spiritual and social benefits (Condon et al., 1995; Durkalec, 2013; Pufall et al., 2011). It is a cultural anchor, reaffirming Inuit identity and connection to the land and strengthening social relationships through food sharing practices. Lake Melville is an important area for harvesting country food for Inuit living in Rigolet and the Upper Lake Melville communities. As a resident of Rigolet explained:

Lake Melville is very important to us, and the watersheds that connect or flow into Lake Melville. It's been a part of our lives and our families' lives as long as anyone can go back, to days of pre-European contact…It's a very traditional area for travel, for seal hunting, for caribou hunting, goose hunting, trapping, recreation, fish, salmon, trout, rock cods…Lots of people have their cabins in this area. All of the above is what keeps us healthy, it connects us to the land, it gives us our food, it gives us our identity.

–Rigolet resident (Nunatsiavut Government, 2011b)

We get a lot of our food from Lake Melville. In the wintertime, we travel back and forth to North West River and Goose Bay to get our food and groceries.

–Rigolet resident (Nunatsiavut Government, 2011b)

At the same time, contaminants in the Arctic food web are of concern to Inuit who depend on country food for sustenance, and one-fifth of Nunatsiavut households have reported worry about contaminants in country food (Egeland, 2010). For example, contaminants such as mercury and persistent organic pollutants are transported to the Arctic and subarctic from southern latitudes by atmospheric and oceanic currents, where they bioaccumulate and biomagnify in wildlife with potential health risks for those consuming these species (AMAP, 2011; Donaldson et al., 2010). While nutritional and other benefits exceed risks in most country food species and tissues, minimizing the contaminant load in country foods is critical for maintaining them as a healthy food source.

Ice-based travel

Wildlife in the Arctic and subarctic moves seasonally across the vast landscape, and because of Inuit society's dependence on wildlife species, movement is and always has been an important part of life for Inuit. For much of the year, ice forms an extension of the land, facilitating the ease and extent of land-based travel and connections to country food resources and other communities via a network of routes. Sea ice is often referred to as "highway" by Inuit (Durkalec, 2013; ICC, 2008), and means freedom for ice users.

I can't wait to go on to sea ice and take off. It's freedom, it's my life, it makes me to be alive.

–Nunatsiavut resident (Durkalec, 2013)

After freeze-up, Lake Melville becomes a highway that connects Rigolet with the communities in Upper Lake Melville. As there is no road access to Rigolet, ice provides critical connectivity to goods and services in the larger Upper Lake Melville communities, and facilitates access to important hunting and fishing areas for all residents of the region.

We use [Lake Melville] for coming back and forth, hunting, fishing. It's the only way of travelling in wintertime.

– Rigolet resident (Nunatsiavut Government, 2011b)

Communities across the Canadian Arctic and subarctic including in Nunatsiavut have been reporting concerns about unpredictable weather and increasingly dangerous travel conditions on ice (Ford et al., 2009, 2008; Furgal et al., 2002; Nickels et al., 2006). Recent decreases in the strength, extent, and duration of sea ice cover, changes in the timing of sea ice freeze-up and break-up, and increasing variability and unpredictability of ice and weather conditions due to climate change and variability have been well documented (ACIA, 2005; IPCC, 2014). Indeed, the north coast of Labrador is among the regions showing the strongest climate change signal in Canada: while all coastal regions in Canada's North have shown a decline in summer sea ice coverage in the last four decades, the largest rate of decline was along the north coast of Labrador, where sea ice shrank by 73% in this time span (1,536 km^2 or 17% per decade) (Henry, 2011).

These changes are predicted to increase the frequency and severity of physical health impacts from environmental exposure (ACIA, 2005; Furgal, 2008; IPCC, 2014). There is also evidence that climate change is impacting place attachment in communities in Nunatsiavut by disrupting access to land-based activities and ice-based travel, with negative impacts on mental, emotional, cultural, social, and spiritual health and well-being (Cunsolo Willox et al., 2012; Durkalec et al., 2015). Central to Inuit knowledge and ways of life are adaptation to a changing environment. However, socio-economic factors, the impacts of government policies of colonization and assimilation, remoteness, and connectivity deficits are also constraining adaptive capacity for some communities and individuals (Ford et al., 2010).

1. 4. Hydroelectric development influences on Lake Melville

1. 4. 1. 1970s: Upper Churchill hydroelectric development

After Newfoundland and Labrador joined Confederation in 1949, then-Premier Joey Smallwood began planning to develop the Churchill River, Labrador's largest river. The Upper Churchill hydroelectric development was completed in 1971, and included construction of the 5,428 MW Churchill Falls Power Station near the centre of the Churchill River watershed, the second largest hydro development in Canada and among the largest globally (Lee et al., 2011) (Figure 1.1). The Churchill River was redirected at the site of Churchill Falls, a 75 m high waterfall. A large portion of the Labrador plateau was inundated to create the Smallwood Reservoir, which covers 6,988 km^2 and has a drainage area of approximately 71,700 km^2 (approximately the size of Ireland). The active storage capacity of the reservoir is 30 billion cubic metres, which is enough capacity for the entire spring runoff to be stored in the reservoir. This development is owned and operated by the Churchill Falls (Labrador) Corporation, with Newfoundland and Labrador Hydro Corporation owning approximately two-thirds its shares and Hydro-Quebec owning the remainder.

Over 75% of the drainage from the total watershed area is regulated by the Churchill Falls Power Station, which has reduced the natural flow variability of the lower Churchill River (Joint Review Panel, 2011). The flow through the Churchill Falls Power Station is generally maintained at approximately 1,400 m^3 per second. As a result, flows in the Churchill River are higher in the winter and lower in late spring and summer compared to pre-development conditions.

The Panel for the Lower Churchill project reported major limitations in baseline data for the Churchill River before the changes brought about by the Upper Churchill development. The Panel reported that it received no evidence that the Upper Churchill development was operated with any environmental objectives or constraints. The creation of the Smallwood Reservoir in the 1970s caused methylmercury concentrations to increase in fish in the Churchill River system, including 300 km downstream in Lake Melville (Anderson, 2011). Mercury levels in non-piscivorous fish (non-fish eating, lower trophic level) are now approaching or have returned to background levels, while levels in piscivorous northern pike and lake trout remain elevated in the main stem of the Churchill River, with consumption advisories in effect for these species (Joint Review Panel, 2011). However, as reported by the Panel, our understanding of Upper Churchill impacts on mercury levels in fish in the Churchill River system is limited by several factors (Joint Review Panel, 2011). No baseline data were collected for mercury levels in the Churchill River before the Upper Churchill development commenced, and fish sampling only occurred once in the first 15 years of operations, so peak concentrations may not have been captured. It is not known how the partial regulation of the Churchill River caused by the Upper Churchill development has affected the abundance of harvested fish species in the lower Churchill River, what level of fishing took place before the Upper Churchill development, or the extent to which existing methylmercury contamination has reduced fishing activity on the lower Churchill River. Further, we have a limited understanding of the spatial and temporal extent of mercury effects from the Upper Churchill development on estuarine fish downstream in Lake Melville. Participants in the Lower Churchill EA reported various downstream impacts of the Upper Churchill development, including saltwater intrusion into Grand Lake with adverse effects on certain fish species; changes in the migratory patterns of caribou; and changes in tides and water depths in Lake Melville, with negative effects on navigation.

1. 4. 2. Now: Muskrat Falls and the Lower Churchill hydroelectric development

Overview of the Lower Churchill project

Nalcor Energy, the Newfoundland and Labrador provincial energy corporation, is developing two large hydroelectric facilities on the lower reaches of the Churchill River, one at Muskrat Falls and one at Gull Island (Figure 1.1, Figure 1.2). The first phase of the development, currently underway, involves constructing an 824 megawatt (MW) dam at Muskrat Falls and flooding a 41 km^2 area to create a reservoir of 101 km^2. A 1,100 km Labrador-Island Link will transmit Muskrat Falls power to the island portion of the province and a 170 km subsea Maritime Link will bring a portion of the power from there to Nova Scotia. Emera Inc. will construct, own, and operate the Maritime Link for 35 years in exchange for 20% of Muskrat Falls' power (Emera, 2014). Phase two of the project will involve construction of a 2,250 MW dam and 213 km^2 reservoir at Gull Island by inundating 85 km^2, and additional transmission corridors to link the two Lower Churchill facilities with the Upper Churchill hydro development.

The Lower Churchill project was registered for joint federal-provincial EA in 2006, which was completed in 2011 with the report of the Joint Review Panel. The Panel made 83 recommendations. The federal and provincial governments issued government sanction

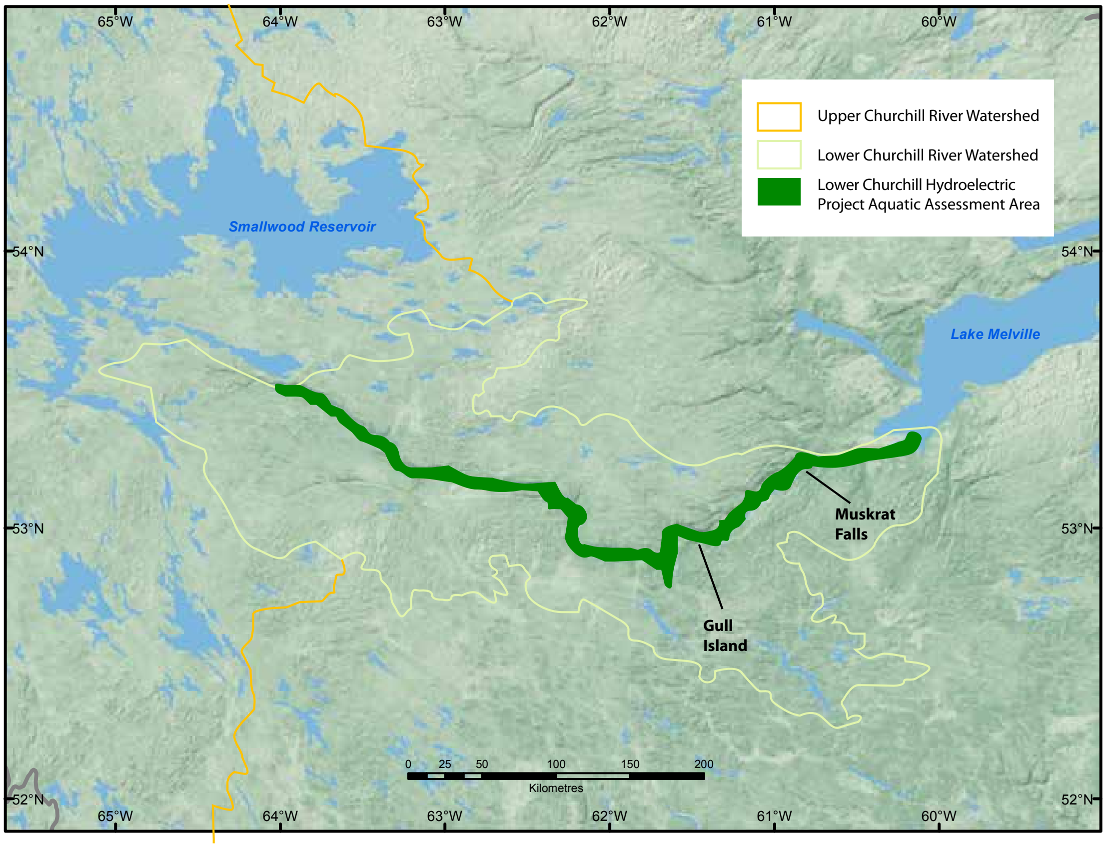


Figure 1.3. Aquatic Environment Assessment Area in the Lower Churchill EIS was the main stem of the Churchill River (dark green filled area). Source: Adapted from Nalcor Energy (2009a, Fig. 2–2, p. 2–16).

in 2012, and Fisheries and Oceans Canada (now the Department of Fisheries, Oceans and the Canadian Coast Guard) and the province issued authorizations in 2013 to construct the Muskrat Falls reservoir and dam.

Construction cost estimates for Muskrat Falls were $7.65 billion in fall of 2015, up from $6.2 billion at the time of project sanction (Fitzpatrick, 2015), with more increases expected (Antle, 2016). None of the power from the Lower Churchill project will be used for meeting energy needs in Labrador; all of it is being exported out of the region to the island portion of the province and Nova Scotia.

Predictions of downstream effects during the EA

Nalcor predicted that, "there will be no change in flow or salinity, water temperature, ice or other physical disturbance beyond the mouth of the Churchill River from this Project" and consequently established the EA boundary to exclude Lake Melville and Nunatsiavut (Nalcor Energy, 2009a, p. 2-16). Figure 1.3 shows the aquatic assessment area employed by Nalcor in the Environmental Impact Statement (EIS), which was limited to the Churchill River main stem. Based on this decision, baseline sampling of Lake Melville and detailed study regarding downstream impacts, including the fate, transport, and bioaccumulation of methylmercury, was not carried out.

Nalcor's prediction was based on two main reported premises: 1) that the mouth of the river is the end of the riverine habitat, and 2) that with few potential exceptions, "Goose Bay dilutes any effects originating from upstream to 'no measureable effects' level on the key indicators" (Nalcor Energy, 2011, p. 3). The term "no measurable effects" was defined as changes occurring within the range of natural variability. Nalcor predicted that:

Dilution in the area of Goose Bay is caused by freshwater inputs from a number of sources and by mixing with the salt water that enters Goose Bay from Lake Melville...Other biological (e.g. uptake), physical (e.g. settling) and chemical (e.g. photochemical) processes not accounted for in the modelling will also tend to dampen any effects going downstream. The dilution predictions in the EIS are further refined by a modelling exercise conducted using the MIKE3 dispersion model (Oceans 2010). As stated in the EIS, the shallows at Goose Bay Narrows act as a hydraulic control that slow exchange with Lake Melville (Hatch 2008a) and likely provide at least a partial barrier to plankton and fish because of the abrupt vertical mixing of fresh and saline water at this location. In the case of increased mercury in fish (a potential effect of the project as predicted in the EIS), the main pathways are water, total suspended solids (TSS), plankton and fish. Water, TSS and plankton are progressively 'diluted' going downstream from Muskrat Falls and most sediment will settle out along the way; the [Goose Bay] Narrows will further 'block' sediment, plankton, and fish to some degree. Many freshwater species cannot tolerate abrupt changes in salinity thus limiting their movement past the Narrows.
(Nalcor Energy, 2011, p. 3)

Nalcor's assumption of dilution relies on limited modelling that largely does not draw values from baseline sampling (Joint Review Panel, 2011). Specifically, the model of mercury dispersion (Oceans, 2010) did not include any biological processes of mercury accumulation in Lake Melville or direct measurements of methylmercury levels in water or plankton, even though the majority of methylmercury bioaccumulation (x10^3 to x10^5) occurs between seawater and plankton (see section 6.3). Nalcor determined mitigation measures based on these assumptions, including the utility and necessity of full clearing to reduce methylmercury inputs downstream. Nalcor concluded that in addition to technical issues, "reservoir vegetation clearing and soil stripping would not be cost effective if carried out strictly to reduce fish mercury levels" (Nalcor Energy, 2009b, p. 7). As such, it proposed a partial clearing option.

Nalcor also predicted that the thickness and stability of river ice below Muskrat Falls would not change as a result of the project because flow levels would be similar to current conditions. However, Nalcor did expect freeze-up to be delayed by two weeks or up to three weeks under climate change scenarios and break-up to be delayed by approximately one week. Nalcor predicted that any changes to the ice regime in Goose Bay and Lake Melville would be localized and small (Nalcor Energy, 2011, 2009c).

Numerous participants in the EA raised concerns about the adequacy of Nalcor's downstream assessment and the exclusion of Goose Bay and Lake Melville, and questioned Nalcor's predictions, including Fisheries and Oceans Canada and the Nunatsiavut Government. The Panel reported concerns related to potential changes to erosion and deposition downstream, mercury accumulation, and fish entrainment. Nalcor's boundary between the river and estuary environment was criticized as being unscientific and not supported by Inuit knowledge. Concerns were also raised related to changes in seasonal flow and salinity in the river, and impacts on the ice regime and ice-based travel in Lake Melville.

Panel conclusions regarding downstream effects

Limited information in the literature regarding downstream impacts of hydroelectric projects at northern latitudes meant that most of the information available to the Panel came from Nalcor's modelling work. The Panel reported that existing gaps in knowledge were, "likely compounded by Nalcor's decision to place the study boundary at the mouth of the river and therefore not carry out baseline sampling in Lake Melville" (Joint Review Panel, 2011, p. 88). The Panel evaluated Nalcor's mercury predictions:

The Panel concludes that Nalcor's assertion that there would be no measurable effect on levels of mercury in Goose Bay and Lake Melville has not been substantiated...The Panel also concludes that Nalcor did not carry out a full assessment of the fate of mercury in the downstream environment, including the potential pathways that could lead to mercury bioaccumulation in seals and the potential for cumulative effects of the Project together with other sources of mercury in the environment. (Joint Review Panel, 2011, p. 88)

The Panel is not convinced that all effects beyond the mouth of the river will be "non-measurable" as defined by Nalcor (within natural variability). The Panel concludes that downstream effects would likely be observed in Goose Bay over the long term caused by changes in sediment and nutrient supply and in water temperature. Effects in Lake Melville are more difficult to predict on the basis of existing information. The Panel acknowledges that there is difficulty in accurately predicting the scale of effects given the absence of long-term ecological studies of the effects of hydroelectric projects in northern environments on receiving waters. However, the Panel believes that this emphasizes the need for a precautionary approach, particularly because no feasible adaptive management measures have been identified to reverse either long-term adverse ecological changes or mercury contamination of renewable resources. (Joint Review Panel, 2011, p. 88)

The Panel noted that Nalcor did not identify mitigation measures to address downstream effects from mercury other than consumption advisories, and concluded that:

Should consumption advisories be required in Goose Bay and Lake Melville, the Panel concluded that the Project would have significant adverse effects on the pursuit of traditional harvesting activities by Labrador Inuit, including the harvesting of country food. (Joint Review Panel, 2011, p. xxiii)

Because of lack of information, the Panel stated that it was unable to confidently conclude what the downstream ecological effects would be, and recommended that before impoundment, Fisheries and Oceans Canada require Nalcor to carry out a comprehensive assessment of downstream effects subject to federal and independent third-party review and feedback by Indigenous groups and stakeholders (Recommendation 6.7). This assessment was to include baseline mercury data collection in water, sediments, and biota; revised modelling taking into account all possible pathways for mercury throughout the food web to predict the fate of mercury in the downstream environment; quantification of changes to the estuary associated with changes in sediment and nutrient input and temperature changes; and identification of any additional mitigation and adaptive management measures.

The Panel considered full clearing of trees and vegetation from the Muskrat Falls reservoir a methylmercury mitigation strategy, noting that, "the more trees cleared, the more benefits accrue in terms of reducing methylmercury accumulation and greenhouse gas emissions, though gains may be small" (Joint Review Panel, 2011, p. 46). The Panel found full clearing to be technically and economically feasible, and recommended that Nalcor be required to carry out full clearing to prepare the reservoir for flooding (Recommendation 4.5).

The Panel agreed with Nalcor that the project is unlikely to have adverse effects on ice conditions in Lake Melville, but recommended that conditions and the timing of freeze-up and break-up should be monitored given the uncertainty regarding potential effects on an ice bridge important to Mud Lake residents, uncertainty about how to mitigate effects and at whose expense, and the permanency of any impacts on winter travel from the project.

Federal and provincial government responses and actions

The federal and provincial governments responded to the Panel report in March 2012. The federal government determined that significant adverse environmental effects are justified by the benefits of the project.

Regarding recommendation 4.5, full clearing of the Muskrat Falls reservoir, the federal government deferred to the province, and the province rejected the recommendation based largely on an economic rationale and the assumption of likely insignificant reductions in mercury levels from additional clearing.

Regarding recommendation 6.7, assessment of downstream effects, the province deferred to the federal government. The federal government agreed with the intent of the recommendation, but only directed Fisheries and Oceans Canada to require that Nalcor collect additional baseline data on methylmercury accumulation in fish and seals within the reservoir and downstream before flooding, as opposed to a comprehensive assessment of downstream effects as the Panel recommended. Additional downstream baseline sampling by Nalcor related to the downstream fate of mercury has been limited to surveying seal abundance and mercury burden in fish and ringed seal in the lower reaches of Lake Melville and Goose Bay, mostly outside the boundaries of Nunatsiavut (Amec Foster Wheeler, 2015). The federal and provincial government have carried out water quality sampling, but only at one location in Lake Melville (Amec Foster Wheeler, 2015). Fisheries and Oceans Canada issued a Fisheries Act Authorization for construction of the Muskrat Falls reservoir and the provincial Department of Environment and Conservation issued a Permit to Alter a Body of Water for construction of the Muskrat Falls dam, both in July 2013.

Nunatsiavut Government's response

The Nunatsiavut Government participated actively in the EA process, making over 30 submissions to the Panel. The core of the Nunatsiavut Government's view at present and throughout the EA has been that objective, transparent, and credible science and assessment is needed to support good environmental decision making, particularly as Inuit health, culture, and rights are at stake.

The Nunatsiavut Government objected strongly and repeatedly to the exclusion of Lake Melville from the EA, asserting that predictions of impacts made without a sound understanding of the system being affected are unreliable, and an adequate and protective monitoring program cannot be put into place for a system that is not well understood. The exclusion of Lake Melville meant that the EA did not rigorously assess impacts of the project on Inuit territory or on a number of key indicators and valued ecosystem components of importance to Inuit, such as seal health and Inuit health. Inuit are experts in their environment, and the view of the Nunatsiavut Government is that this knowledge was not valued or used to inform the EA design, methods, and findings.

Despite the consensus amongst the Panel and experts from Fisheries and Oceans Canada that Nalcor's downstream mercury predictions were unsubstantiated and not scientifically sound, government sanction decisions were based on this limited information. In the subsequent regulatory process, government did not implement the Panel's recommendation for a comprehensive downstream assessment, choosing instead to only require limited sampling. The Nunatsiavut Government filed motions for judicial review of the permitting decisions by the federal and provincial governments based on inadequate consultation and accommodation, but these were dismissed at the federal and provincial Supreme Court levels in 2015, in part related to the timing of these motions. The provincial court found that once the province released the project from EA in 2012, concerns about mercury accumulation impacts and mitigation, monitoring, and compensation measures "move[d] to the background, in a legal sense" (Nunatsiavut v Newfoundland and Labrador, para 160). However, the Court also found the province's dismissal of the Panel's recommendation for full clearing "surprising" (para 87) and its focus on economic rationale "somewhat shallow" (para 86).

... [T]he nature of the issues – including the lack of reliable data on the potential effects of mercury on the fish harvested and consumed by the Inuit – reinforces the need for recognition and acceptance of the reality and value of the Inuit rights in question and the need for a real and ongoing commitment to take all reasonable steps to minimize adverse effects and to establish meaningful measures to address and compensate for such effects should they arise in the future.

The rights held by the Inuit are real. They cannot be ignored. The Inuit invested much time and effort in the Joint Review Panel process and continue to seek to minimize the effects of the project on those rights. There is disagreement over what that effect may be in years hence. But respect and honourable dealing requires the province to look past the continuing disagreement and to at all times in its decision-making carry out a good faith balancing of the rights and interests of the Inuit and the rights and interests of the province. (Nunatsiavut v. Newfoundland and Labrador, para 167–168)

The lack of baseline data for and understanding of the Lake Melville system and how it may be affected by the Lower Churchill project has been a significant and ongoing issue. As a result, the Nunatsiavut Government organized the Lake Melville: *Avativut, Kanuittailinnivut* research program to facilitate the gathering of objective and credible baseline information on the Lake Melville ecosystem to fill critical gaps in knowledge. The following report is a culmination of this work, and documents knowledge gathered by a team of international scientists on current baseline ecosystem functions and expected future changes related to climatic and development stressors.

Deploying moorings on Lake Melville.

Credit: Rodd Laing

2. PHYSICAL LAKE PROCESSES

Entcho Demirov and Brad deYoung *Memorial University of Newfoundland*

2.1. Introduction

Lake Melville is a large and complex land-locked estuarine fjord that is sensitive to changes in the atmosphere and ocean. As its waters are derived from both the ocean and the large river systems that discharge into the lake, the oceanographic characteristics of Lake Melville are strongly influenced by tidal flow, river discharge, wind-forcing and ice.

The first comprehensive oceanographic observational cruise in the Lake Melville was conducted by scientists in 1949 to 1950 and published in two reports (Nutt, 1951 and Coachman, 1953), providing the first description of the tidally driven estuarine system in Lake Melville. Few studies on the oceanography of Lake Melville have been conducted since this time (see Cardoso and deYoung, 2002). The introduction of the Upper Churchill hydroelectric development on Lake Melville's main tributary over four decades ago has influenced river and lake dynamics, but knowledge regarding the nature and extent of these influences on the physical oceanography of Lake Melville is limited. Very few measurements have been made near the Rigolet Narrows, a shallow rock sill that separates Lake Melville from Groswater Bay and the Atlantic Ocean (Figure 2.1) despite the critical significance of this sill on the oceanography of the lake. New observations are crucial for understanding Lake Melville dynamics and accurately assessing possible effects of anthropogenic stress and climate change on the lake environment.

We present observations from a one-year monitoring program in Lake Melville. This is the first time that currents near the sill were measured and it also represents the only full year of observational data from the lake in recent years. These observations allowed us to estimate the parameters of tidal flow in the lake, seasonal variability of vertical temperature, salinity distribution, and intensity of the non-tidal flow.

We also present results from model simulations of the impacts of variations in Churchill River discharge associated with the development of the Upper Churchill hydroelectric project in 1971 on dynamics in Lake Melville.

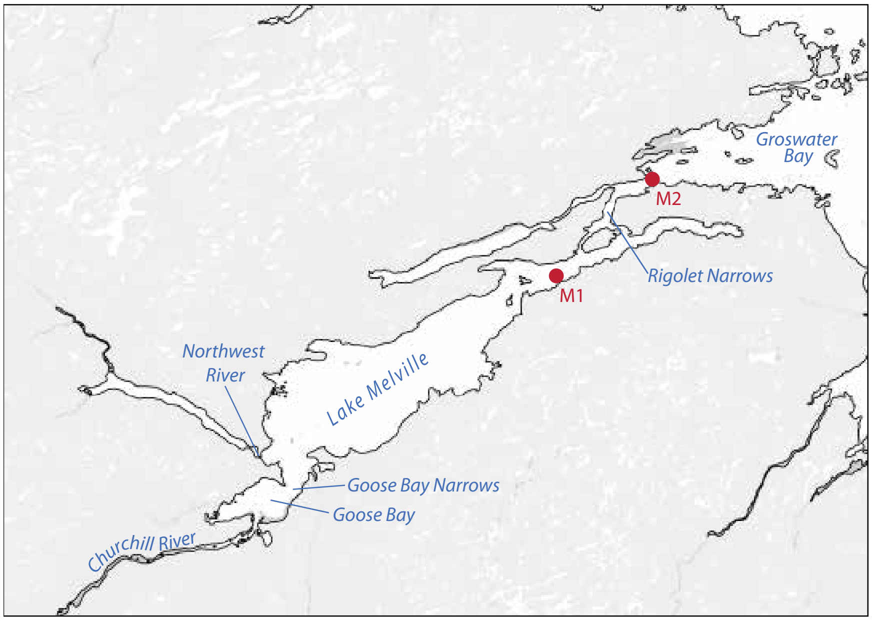


Figure 2.1. Locations of the two current meter moorings (M1 and M2) relative to the sill at the Rigolet Narrows. Source: Adapted from Lu et al. (2013).

2.2. Methods and approach

This physical oceanographic study is part of a commitment by the Department of Physics and Physical Oceanography at Memorial University to long-term observational and modelling research activities in Lake Melville, first initiated about fifteen years ago. Previous work has included: 1) a systematic data archive and inventory of previous observational studies in Lake Melville (Cardoso and deYoung, 2002); 2) development of a modelling system for the physical and environmental characteristics in the lake (Cardoso, 2003); and 3) development of observational infrastructure as well as data and model studies of Lake Melville.

For this study, we conducted one year of observational monitoring of physical characteristics of Lake Melville. Based on previous knowledge and experience, two areas were selected on either side of the sill at the Rigolet Narrows, with one set inside the lake and the other just outside the sill, east of Rigolet (Figure 2.1). Two moorings were deployed that collected observations of major physical characteristics in the water column from July 2012 to July 2013. The mooring observations focused on two key processes for which we had no previous observations: 1) the exchange between the lake and the ocean and 2) the transformation of the tidal flow by the shallow sill at the Rigolet Narrows. The data included observations of currents using Acoustic Doppler Current Profilers (ADCP), and of temperature using thermistors, from very near the bottom to very near the surface at regular temporal intervals. We also collected data on the hydrographic conditions in the lake using conductivity-temperature-depth (CTD) casts at 10 stations in 2012 and 41 stations in 2013 to measure temperature, salinity, and density from outside the sill to the head of the lake. For additional details on observational methods, see Lu et al. (2013, 2014).

Results from the one-year observational mooring program were used to initialize and verify numerical models of Lake Melville. The model development was focused on resolving the important processes that govern the lake – ocean exchange, tides, and river discharge – and on developing a realistic representation of the vertical water column and flow characteristics inside the lake. Two sources of freshwater discharge to Lake Melville are included in the model: the Churchill River and the Northwest River. Two model simulations were conducted – the first one driven with river discharge in the lake before 1971 and the second one driven with river discharge after 1971, when the Upper Churchill hydroelectric development began operations. All other forcing functions for the model are the same in the two experiments and calculated as representative for the year 1985. The atmospheric temperature and precipitation in this year were found to be close to average for the region. The availability of observations from the one-year mooring program allowed us to validate the models and adapt their parameters and forcing for the specific conditions of the Lake Melville environment.

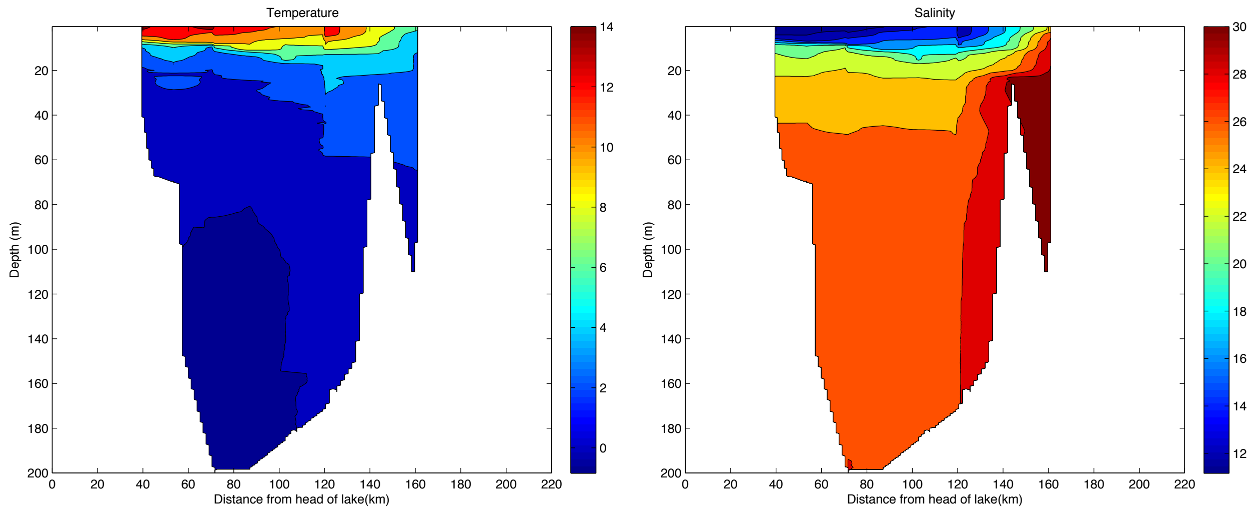


Figure 2.2. Temperature (°C) and salinity (psu) along the axis of the lake in June 2012. Source: Lu et al. (2013).

2.3. **Understanding physical dynamics in Lake Melville**

Lake Melville dynamics driven by large freshwater input and strong tidal flow

The physical oceanographic measurements confirm our basic understanding of Lake Melville dynamics as being driven by two key influences. First, the enormous freshwater input, among the largest in eastern North America, lowers the surface salinity and also drives surface water out of the lake. The flow below the surface layer transports saltwater from the Labrador Sea in the opposite direction, into the lake, where the denser water sinks and renews deep waters. The volumes of freshwater outflow and saltwater inflow over the sill are in approximate balance, so the volume of freshwater inputs to the lake and subsequent freshwater outflow are directly related to the volume of deep-water renewal. Second, complicating the dynamics, incredibly energetic tidal mixing takes place at the sill at the Rigolet Narrows, where currents reach 3 to 4 m/s. Our mooring observations and hydrographic measurements improved our understanding of the seasonal character of this oceanography.

Stratification in the lake is very strong in the upper part of the water column and is in general quite weak below depths of 50 m (Figure 2.2). Surface salinity is strongly influenced by river discharge, but deep salinity is controlled by the salinity of the ocean waters just outside the sill and the mixing of those waters with outflowing surface waters as they collide at the entrance to the lake at the Rigolet Narrows. There is quite a strong gradient in water properties on either side of the Rigolet Narrows.

A sharp decline in mean currents occurs from the surface where they approach 0.5 m/s to depths below 50 m where they are generally quite small, less than 0.1 m/s (Figure 2.3). The variability is, however, quite large; significant currents, greater than 0.2 m/s at depth and greater than 0.7 m/s near the surface, can be observed at any time of the year. Tidal currents account for approximately 55% of the variance in currents below

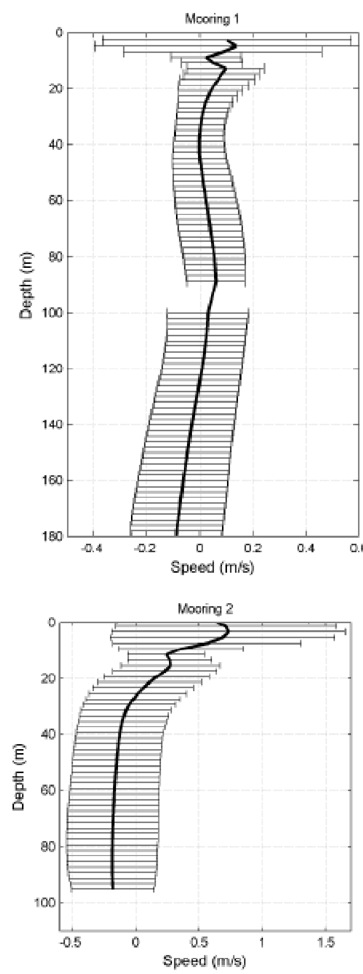


Figure 2.3. Mean currents (solid line) and variations in current (horizontal lines) on either side of the sill at the Rigolet Narrows. The variation is shown as a single standard deviation.

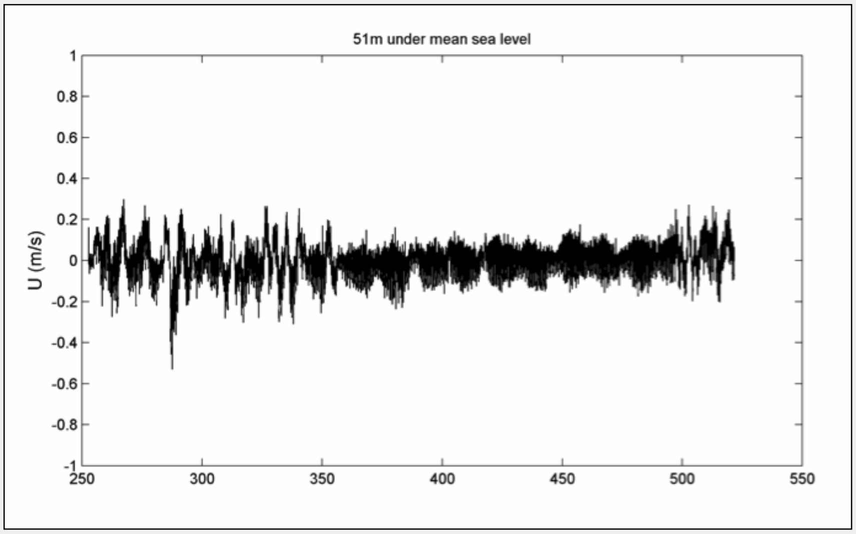


Figure 2.4. Currents from September 2012 to June 2013 in Year Days (counted from 1 January 2012) at 51 m depth at M1 inside the sill in Lake Melville. The U component represents the horizontal velocity with direction along the axis of the lake (i.e. movement in and out of the lake). The drop in currents from December 2012 (around day 350) to late April 2013 (day 500) is because of the formation of ice.

the surface layer. Surface water exchanges relatively quickly – in the order of tens of days. We directly observed deep-water renewal in the lake, finding that dense water entered over the sill at the end of the year leading to the exchange of water at the bottom of the lake. Our results and the observation that no anoxic events (water without oxygen) have been found in the deep waters of the lake indicate that deep-water renewal events are quite common. We postulate that such renewal events occur over an extended period of time annually. Overall, the residence time of water (how long it takes to leave the lake) increases with depth, and the flushing time of the lake is estimated to be 192 days based on available observations. We found that wind-forced and tidal currents in the lake change significantly in the presence of ice. In the summer, when there is no ice, the strongest tidal currents are observed near the surface, in the top 10 m of the water. In the winter, when ice is present, the tidal currents increase in strength from the surface to the bottom. Outside the lake, where open water is common even in winter, there is little seasonal signal to the tidal currents.

The currents over the year show the strong influence of ice in the winter (Figure 2.4). The ice has two primary effects. The most obvious is the decoupling of the currents from the wind field. The variability in the currents that is associated with the wind nearly disappears in the winter from day 350 to day 500 (several months into 2013). The ice also strongly limits the surface tidal response inside the lake during the winter. These two effects mean that the lake is much 'quieter' in the winter with weaker currents and less mixing of water, both in the lake and at the sill.

Influence of Upper Churchill hydroelectric development on river discharge

In 1971, the Upper Churchill hydroelectric development began operations on the Churchill River, which flows into Lake Melville. While findings from Chapter 3 indicate that climate has a much stronger influence on the ice regime in Lake Melville than Churchill River discharge, changes in river flow also have the potential to influence ice cover, though mechanical disruption and the influence of salinity on the lake. To improve our understanding of these potential influences, we conducted model simulations to identify the response in physical characteristics of Lake Melville to the changes in river discharge related to the Upper Churchill hydroelectric development. In particular, we focused on two major groups of physical factors that influence ice that may be affected by changes in river discharge: 1) changes in dynamics and current velocities in the region adjacent to the Churchill River mouth, and 2) thermodynamic changes associated with variations in surface layer salinity. Here we describe how these two groups of factors impact ice production and ice transport in the lake.

Evidence from our study demonstrates that the annual mean river discharge after 1971 is very close to the annual mean river discharge before 1971, at about 1800 m^3/s. The major change in river discharge between these two periods is associated with variations in the seasonal cycle. After 1971, the river discharge significantly increases in the winter season (Figure 2.5) when the hydroelectric power facility is working actively. The large pulse in river discharge in late spring or early summer is also significantly reduced after 1971 (Figure 2.5).

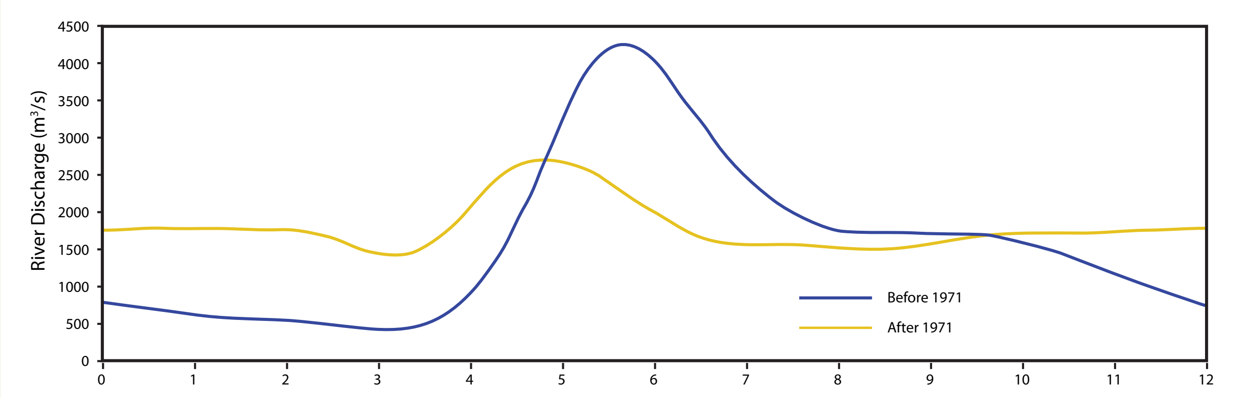


Figure 2.5. Variations in river discharge from the Churchill River due to the impact of the Upper Churchill hydroelectric facilities built in 1971. The figure shows the monthly mean Churchill River discharge calculated for two periods of time: before (blue curve) and after (yellow curve) 1971.

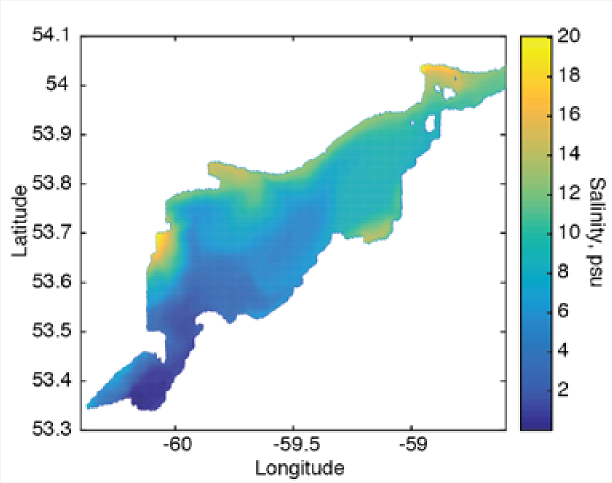


Figure 2.6. Model simulation of annual mean surface salinity (psu) of Lake Melville.

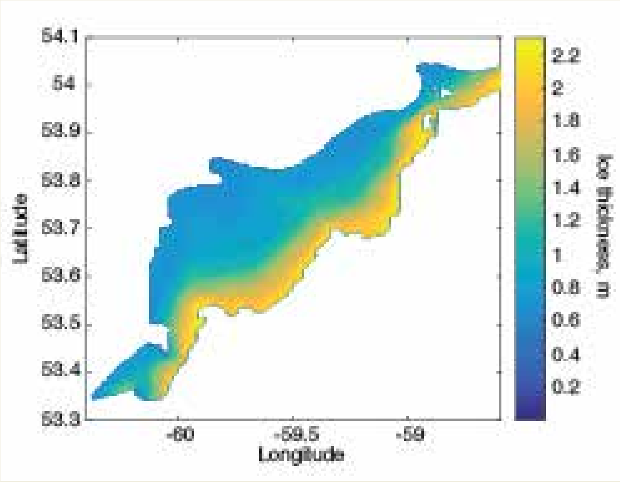


Figure 2.7. Model simulation of monthly mean ice thickness (m) in Lake Melville for February.

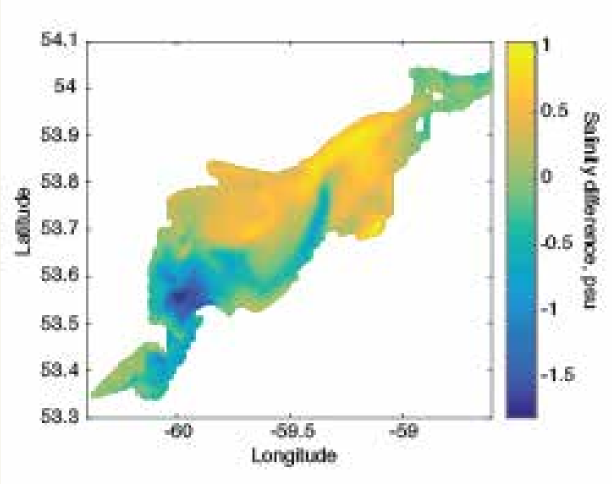


Figure 2.9. Winter season: Differences in salinity (psu) in the two model experiments calculated with river discharge after 1971 minus salinity in the model experiment with river discharge before 1971.

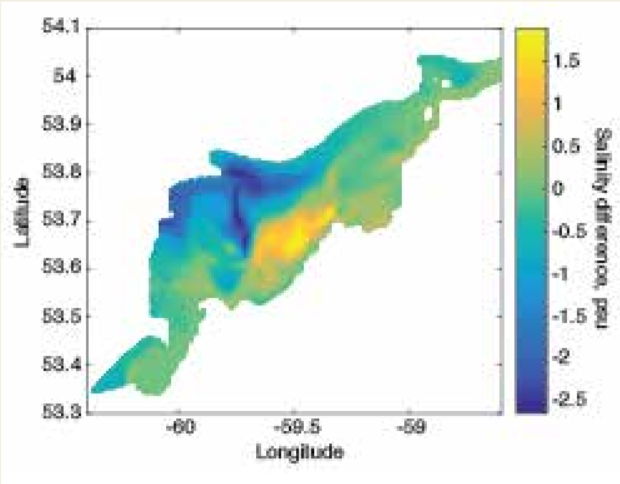


Figure 2.10. Summer season: Differences in salinity (psu) in the two model experiments calculated with river discharge after 1971 minus salinity in the model experiment with river discharge before 1971.

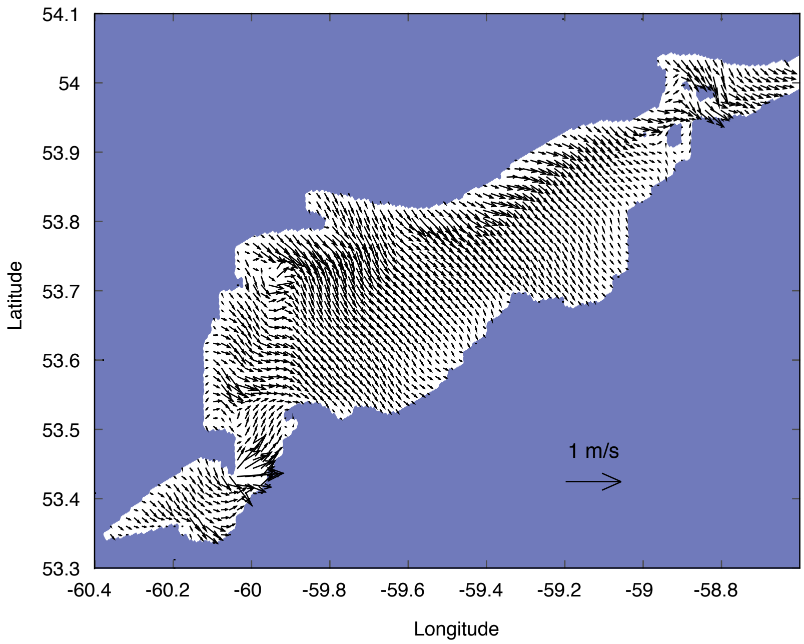


Figure 2.8. Model simulations of winter (January–March) mean ice velocity (m/s) in Lake Melville.

Our model indicates that the immediate effects of the reduction in the amplitude of the seasonal cycle of the river discharge after 1971 are localized in the western part of the lake, in the Goose Bay area, and strongly influence the dynamics of the region in the vicinity of the Churchill River plume. From a temporal perspective, the differences in the river discharge before 1971 and after 1971 have the largest magnitudes in the winter and summer (Figure 2.5). The model simulations suggest that the change in river discharge in the winter season has impacts on ice thickness and transport after 1971. Although Lake Melville remains stratified throughout the year, the model experiment indicates that variations in river discharge in the warm part of year altered the horizontal distribution of surface salinity, the water column stability and intensity of vertical mixing in all parts of the lake after 1971. In the summer season such variations in the dynamics can potentially influence the processes of primary production.

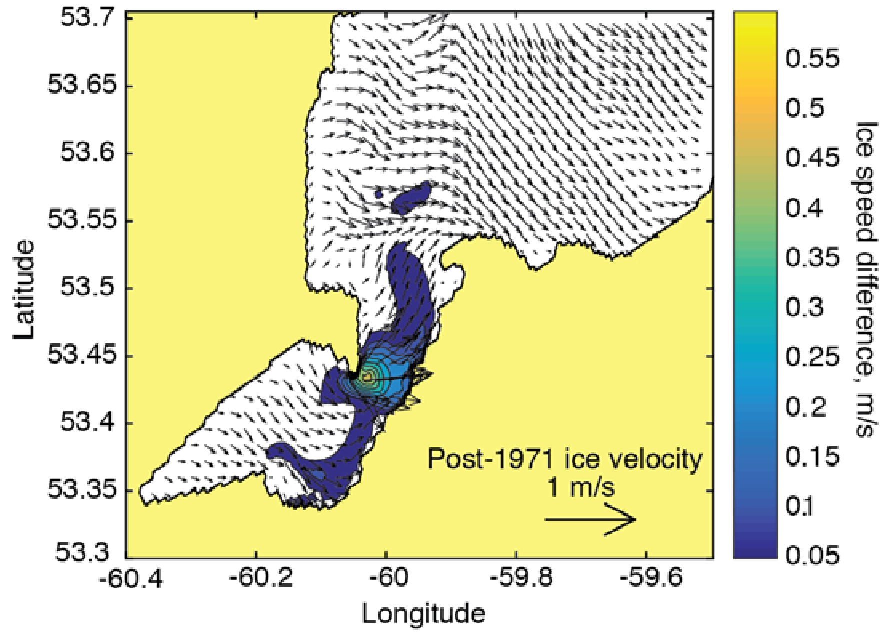
Influence of salinity and currents on ice thickness and transport in Lake Melville

The model indicates that the surface freshwater discharge from the Churchill River moves through Lake Melville via two major branches – the first one northward and along the west coast of the lake and the second northeastward along the south coast of the lake (Figure 2.6). Areas of slightly elevated salinity of about 16–20 psu, still much lower than average ocean water salinity of approximately 35 psu, are present in some isolated shallow coastal areas. These maxima form mostly in winter in some shallow areas of the lake and are due to salt being expelled from the ice during freezing.

Simulated ice thickness is greatest along the southern coast of Lake Melville (Figure 2.7). The salinity in this region is influenced by freshwater originating from the discharge of the Churchill River (Figure 2.6). Freezing temperature decreases with an increase in salinity; conversely, water freezes more easily (i.e. at a higher temperature) at a lower salinity. Therefore, the same winter cooling would produce more ice in areas of low salinity than in saltier waters. In addition to low salinity (see Figure 2.6), another factor contributing to the greater ice thickness along the southern coast of the lake is ice transport (Figure 2.7).

Ice transport is normally driven by surface currents and near surface atmospheric winds. The model simulation indicates that the complex interaction of these two factors in Lake Melville results in ice transport that in most of the lake has a predominantly south-southeastern orientation (Figure 2.8). Modelled ice transport is locally intensified in the vicinity of the mouth of Churchill River and causes a strong export of ice towards the southern part of the lake. In total, the ice velocity combines with low salinity to contribute to the increase in ice thickness along the southern coast of the lake (Figure 2.7).

Figure 2.11. Differences (the contours) in ice speed in the two model experiments with river discharge after 1971 minus ice speed in the model experiment with river discharge before 1971. The arrows show the ice velocity computed with river discharge after 1971.



Influence of Upper Churchill hydroelectric development on Lake Melville ice

We investigated how changes in Churchill River discharge triggered by the Upper Churchill hydroelectric development starting in 1971 influenced surface salinity, ice transport and ultimately the ice thickness in Lake Melville. While stratification in Lake Melville remains stable year-round, the model experiment indicates that increased river discharge in winter since 1971 has had a minor influence on salinity in the southern part of the lake during this season, extending east along the lake's southern coast (Figure 2.9). The difference in salinity in this region varies between -1.0 and -1.5 psu. In the northern part of the basin, the difference in winter salinity is relatively weak and positive.

The model experiment indicates that the reduction in river discharge in the summer season after 1971 causes a small increase in salinity in the area where river discharge waters spread, which would again not affect the strong stratification in the lake. The model indicates that the increase in salinity in summer is highest in the southern part of the lake. In the northern part, the change in salinity in summer is negative. In the vicinity of the discharge of Churchill River waters, salinity is more stable; after 1971 it remains close to the salinity of before 1971.

The model indicates that ice velocities change after 1971 primarily in the area near the mouths of Churchill and Northwest Rivers (Figure 2.11). The main cause of these changes is the rise in water level driven by intensified winter river discharge.
The increase in modelled ice velocity in some parts of these regions reaches up to 50 cm/s. This increase contributes to more intense export of ice into the southern part of the lake. Further, it is associated with more frequent cracking of ice in those areas where the increase in ice velocities is strongest. The model indicates that this cracking results in these areas becoming completely or partly ice-free for a short period more often after 1971.

Figure 2.12 shows the variations in ice between the two experiments forced with river discharge before and after 1971. The difference in ice thickness in the two experiments reflects the changes in the surface salinity and ice velocities. Intensified winter river discharge after 1971 creates areas of decreased salinity (see Figure 2.9), resulting in modelled ice thickness increases by up to 30 cm in the main basin of Lake Melville, east of Goose Bay. In the region of intensified ice velocities near the mouth of the Churchill River and extending eastward (Figure 2.11), the modelled monthly mean ice thickness for February after 1971 decreases by up to 50 cm (Figure 2.12). The model suggests that the intensified dynamics and export of ice from the area around the mouth of the Churchill River in Goose

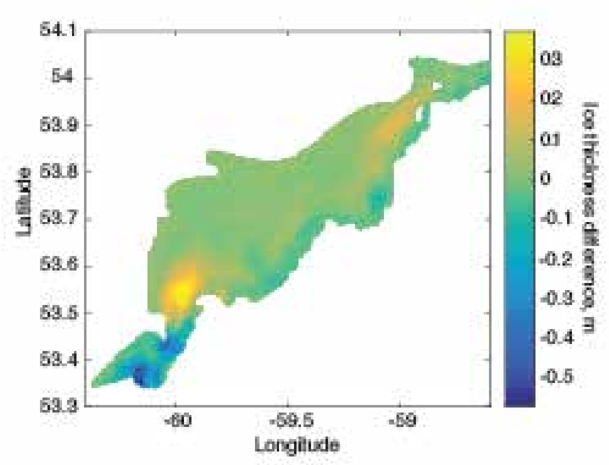


Figure 2.12. Differences in ice thickness (m) in February in the two model experiments calculated with river discharge after 1971 minus salinity in the model experiment with river discharge before 1971.

Bay and stretching to the southern waters of the main Lake Melville basin sometimes causes cracking of ice in this area, resulting in short periods where the water may be ice-free. However, because of strong cooling, ice refreezes quickly in these areas. The model suggests that cracking intensifies after 1971 due to greater ice velocities caused by increased winter river discharge. This increases the occurrence of ice-free periods and decreases the modelled average monthly ice thickness near the mouth of the Churchill River by approximately 50 cm. While the impact on ice travel and safety is difficult to assess based on these findings, we postulate that intensified cracking and transport of ice in the Goose Bay area and the Goose Bay Narrows observed in our models could influence ice strength and stability in those areas. These model findings need to be verified through empirical observation.

Conclusions

In summary, model experiments indicate that changes in the river flow have an influence on the oceanographic and ice characteristics of Lake Melville. Future changes in the freshwater river discharge, the ocean conditions outside the Rigolet Narrows and wind-forcing and air temperature will continue to influence the environmental conditions, and in particular the ice conditions, of Lake Melville.

The model simulations also indicate that the dynamic processes in the vicinity of the shallow sill at the Rigolet Narrows are of crucial significance for the lake-ocean exchange. Observations and model simulations demonstrate that this is a region of intense tidally-driven vertical mixing, inflow and sinking of salty ocean waters. These processes have a strong impact on water renewal inside the lake and are strongly dependent on variations in the intensity of estuarine circulation and on variations in river discharge.

Changes in river flow have the potential to alter the ice regime in Lake Melville. Results related to climate influences on the Lake Melville ice regime show some weak indications that volume of Churchill River flow can influence the timing of ice cover, but that climate has a stronger influence (see Chapter 3). Our results address a different aspect of the influence of river flow on the ice regime in Lake Melville, and show that changes in the seasonality of flow appear to have an influence on salinity, ice transport, and ice volumes in specific areas of the lake.

By developing model experiments of changes in Churchill River flow on the downstream environment, we address current limitations in our knowledge of existing hydroelectric development impacts on the Lake Melville system. We show that despite similarity in total annual flow volumes before and after the Upper Churchill development, changes in the seasonality of flow appear to have influenced both ice velocities and salinity in some areas, causing some increases in ice volume in southern parts of Lake Melville and decreases in ice volumes in the area from the mouth of the Churchill River, through Goose Bay, and to the southern part of the Lake Melville basin in winter. The findings presented here also may explain some of the observations made by Inuit and presented to the Panel regarding changes in Lake Melville since the Upper Churchill development was established, although findings indicate that climate has had a stronger influence on the Lake Melville ice regime than Churchill River discharge. These reported changes include somewhat elevated salinity in some parts of the lake; weaker ice formation, including related to changes in salinity; changes in ice transport; faster and earlier ice breakup; weaker tides; and lower water levels.

2.4. **Potential future changes to physical dynamics in Lake Melville**

The simulation of the effects of past changes following the Upper Churchill project in 1971 can inform our understanding of how any future changes in river discharge from the Lower Churchill project may affect Lake Melville dynamics. Changes in the amount and seasonal timing of freshwater inflow can potentially influence the formation of ice in the lake, the mixing of water in the lake and over the sill at the Rigolet Narrows, and the residence time of water in the lake. Our comparison of the Lake Melville response before and after changes in river discharge from the Upper Churchill development in 1971 indicates two major potential impacts of future variations in the river discharge from Muskrat Falls: 1) slight variations in wintertime salinity in the southern part of the basin; and 2) variations in ice and freshwater export from the area around the Churchill River mouth.

Our model experiments indicate that past changes in Churchill River flow have resulted in impacts downstream on salinity and ice production and transport in Lake Melville, which again are not significant enough to affect the stable year-round stratification in the estuary. Changes in river discharge after 1971 show areas of decreased wintertime salinity and thus increased ice volume, and other areas of increased ice transport and related decreases in ice volume (Figure 2.12). The large magnitude of the seasonal shift in river flow due the Upper Churchill development, which has led to a significant flattening of the annual hydrograph, may mean that the most significant downstream impacts of flow change are already being experienced. However, not all the river flow is regulated by the Upper Churchill development; approximately 25 to 30% of the flow is contributed by downstream tributaries and is unregulated. As there are some additional changes in spring flow projected post-Muskrat Falls, and more of the flow will become regulated, there is the possibility that further flow changes may enhance the existing hydroelectric development impacts indicated by our model experiments.

The exact nature and extent of possible impacts in Lake Melville due to alterations in future flow is difficult to determine without additional modelling that also considers the influence of changing climatic conditions. However, despite the widespread use of numerical models for making environmental predictions, the quality and realism of model simulations degrades quickly if some of the elements of input information are not available or are of poor quality. As such, continued detailed monitoring of river flow and key physical processes in the river and lake environment are critical.

Winter travel on the Nunatsiavut coast.

Credit: Agata Durkalec

3. CLIMATE

Joel Finnis and Merran Smith *Memorial University of Newfoundland*

3.1. Introduction

To improve understanding of Lake Melville's relationship to local climate, we must first quantify local climate variations and change. Prior to the beginning of the Lake Melville project, there had been no detailed climatological analysis for the region since the late 1990s (Banfield and Jacobs, 1998). At that time, Labrador showed no signs of ongoing climate change, even as the majority of the Arctic and subarctic were changing at a significant rate (Serreze et al., 2000). The importance of updating regional climate knowledge was highlighted by a number of unusually warm years since 2000, which together suggested Labrador was rapidly aligning with warming trends observed in surrounding areas. Of particular concern were the alarmingly warm winters of 2009/10 and 2010/11 (Finnis and Bell, 2015; Way and Viau, 2015), which saw frequent, prolonged thaws affecting many Labrador communities (Figure 3.1).

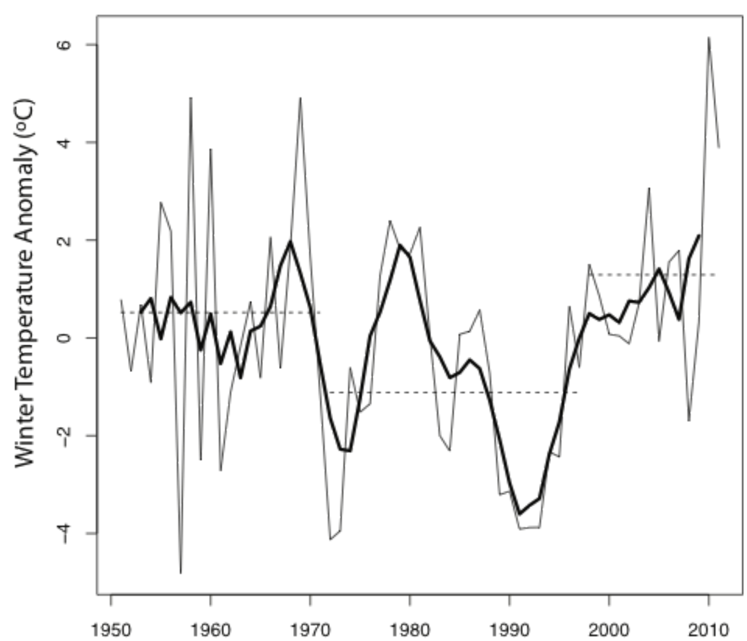


Figure 3.1. Time series of mean winter temperature anomalies (departure from long-term average), averaged over Labrador. Thin black line gives the year-to-year values, while the thicker line gives the 5-year running average. Dotted line is the mean winter temperature during each regime.

3.2. Methods and approach

Through detailed analyses of climate station data, atmospheric reanalyses, and Canadian Ice Service (CIS) ice charts for locations on Lake Melville (Figure 3.2), we updated our understanding of Labrador climate dynamics and their relationship to ice conditions on Lake Melville. The majority of our work is based on a regionally representative temperature data set based on the National Center for Atmospheric Research/ National Centers for Environmental Prediction reanalysis (Kalnay et al., 1996), a roughly 65 year data set that represents our 'best guess' of weather conditions at six hourly intervals. This data set has been supplemented where appropriate with bias-corrected records from Labrador climate stations (Vincent et al., 2012). Change point analysis of this data set was used to identify distinct climate 'regimes' affecting Labrador, while generalized linear models were used to identify/quantify contributions to these regimes from various natural sources (e.g. shifts in atmospheric circulation). Results subsequently guided analysis of weekly CIS ice chart data, to connect climate anomalies and regimes to changes in the timing of freeze-up and break-up across Lake Melville.

In order to identify regime start dates, possible regime change points were identified in seasonally and annually averaged temperature data, following Rodionov (2004). Final regimes represent a compromise between shift dates identified in different seasons; a detailed description of the method and its application are available in Finnis and Bell (2015).

Attribution of temperature anomalies to natural and anthropogenic forces was based on an adapted version of a regression-based methodology used in similar global analyses (Foster and Rahmstorf, 2011). The addition was a cross-validated stepwise predictor selection approach to building a statistical model, designed to avoid model overfitting. Full details are available in Finnis and Bell (2015).

Analysis of Labrador thaw events is based on the application of a point process statistical model, following the heat wave analyses of Furrer et al. (2010). This treats thaw events as a point process, with the number of events in a season treated as a Poisson distribution, the length of events treated as a geometric distribution, and maximum temperatures in individual events fit to the generalized Pareto distribution. The combined frequency and length distributions were subsequently used to generate a

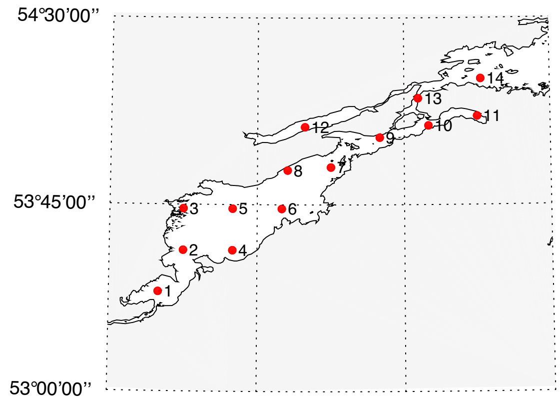


Figure 3.2. Locations used for analysis of Lake Melville ice climatology, using Canadian Ice Service charts.

distribution of total thaw days per season. This was done by using the point process model as a stochastic weather generator; the frequency distribution was randomly sampled to produce 1,000,000 simulated thaw years (number of events per year), and each event in each year was then assigned a length (number of days per event) by randomly sampling from the thaw length distribution.

3.3. Understanding the influences of climate on Lake Melville

Significant natural variability in Labrador is masking impacts of climate change

Results highlight the significant natural climate variability that Labrador experiences, identify causes of this variability, and confirm that the region is experiencing ongoing warming. The Labrador climate record demonstrates pronounced, slow-acting variability; that is, it experiences prolonged periods when temperatures are either well above or well below the long-term average (Finnis and Bell, 2015). These climate 'regimes' can persist for several decades, and arise from natural cycles in: 1) the path of storms through eastern Canada and across the Atlantic, and 2) mean sea surface temperatures in the Atlantic Ocean. These cycles are often discussed in terms of two climate indices: the North Atlantic Oscillation (NAO; storm tracks) and Atlantic Multidecadal Oscillation (AMO; ocean temperatures) (see Box 3.1 and Box 3.2 for more information about the NAO and AMO) (Finnis and Bell, 2015; Way and Viau, 2015).

Table 3.1. Recent climate regimes influencing Labrador. Anomalies relative to the long-term mean temperature are given for each period.

	Regime 1	*Regime 2*	*Regime 3*
Period	*1951–1979*	*1980–1997*	*1998–2011*
Winter	0.16	**-1.27*[a,b]**	**1.29***
Spring	-0.06	**-0.73**	**0.22**
Summer	-0.04	**-0.40**	**0.60**
Fall	-0.13	-0.52	**0.93***
Annual	-0.02	**-0.55**	**0.75***

[a] Statistically significant changes (a=0.1) relative to the prior regime are bolded

[b] Particularly strong changes (a=0.05) relative to the prior regime are marked with an asterisk

Three distinct climate regimes were identified in the Labrador temperature record: a neutral (near-normal) regime from 1951–1979 (Regime 1), a cold regime from 1980–1997 (Regime 2), and a warm regime from 1998 onwards (Regime 3) (Table 3.1).

Findings demonstrate that these climate regimes are strongly tied to natural variability, rather than ongoing climate change. Further, the presence of Regime 2 (cold) acts to hide the impact of ongoing climate change. Removing the estimated contributions of the NAO and AMO greatly reduces the strength of these climate regimes, allowing stronger climate trends to emerge. We compared trends in raw seasonal and annual mean Labrador temperatures over the last six decades, and the residuals remaining after accounting for estimated impacts of natural variability (primarily NAO and AMO) (Figure 3.3). The raw temperature data show weak warming trends in all seasons other than spring; these are much weaker than expected relative to the magnitude of global trends. Larger (positive) and/or more confident trends emerge when the influence of natural variability is removed; this is particularly apparent in winter and spring. This suggests that significant climate change is occurring in Labrador, particularly during winter, but its full impact is hidden by natural variability. This confirms that the naturally occurring NAO and AMO have been obscuring the impacts of global warming in Labrador. Similarly, the change from a cold to a warm regime in 1998 is responsible for much of the recently observed change; this serves to temporarily enhance apparent climate change.

The shift from Regime 1 (neutral) to Regime 2 (cold) is also relatively near the onset of the Upper Churchill hydroelectric development (within 6 years); as a

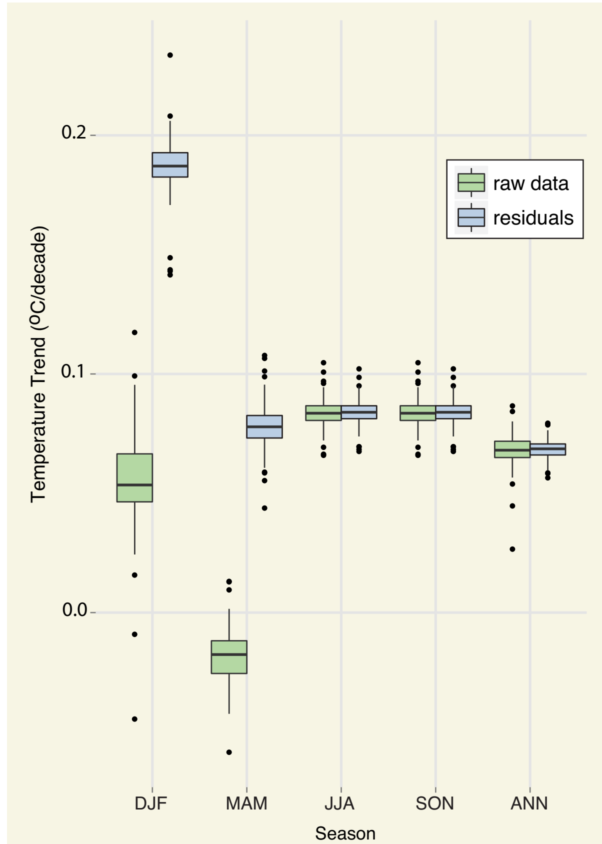


Figure 3.3. Trends in seasonal and annual mean Labrador temperatures over the period 1951–2008. Values are shown for both the original time series ('raw' data) and residuals remaining after the estimated impacts of natural variability, notably the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO). Trends were repeatedly estimated from random subsampling of the total time series to provide uncertainty estimates.

result, it may be difficult to fully separate the impacts of the climate regime shift from those associated with reservoir construction and power generation. Interpreting changes in Lake Melville, the relative impacts of discharge and climate, and safe use of Lake Melville ice requires careful consideration of these regimes and their underlying causes.

Natural variability is contributing to extreme warm winter anomalies in Labrador

The NAO and AMO also explain a large portion of the extreme warm winter anomalies occurring recently in Labrador, with the NAO explaining the majority. The NAO accounts for 45% of significant warm anomalies in Labrador on average, but only 19% of cold anomalies (Figure 3.4). These results show that the NAO played a dominant role in recent warm winter anomalies in 2009/10 and 2010/11; by contrast, climate change

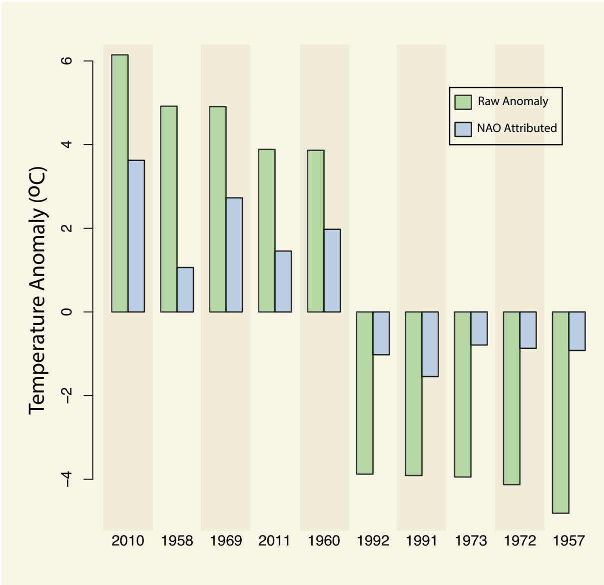


Figure 3.4. Observed temperature anomalies for the five warmest (left) and coldest (right) winter temperature anomalies, and the anomaly attributed to the NAO.

contributed relatively little. Results suggest that NAO-related shifts in atmospheric circulation reduced the flow of cold air from the Arctic and Canadian interior towards Labrador, and may have increased the flow of relatively warm air from the Atlantic, leading to warmer mean temperatures. To the extent that such winters pose a hazard to Labrador residents (e.g. promoting dangerous across-ice travel conditions), the state of the NAO then presents a concern to the region. Given enough time and continuing warming trends, similar warm winters may become more common, requiring less input from a favourable NAO to produce adverse conditions.

These NAO-related changes also encouraged frequent, persistent thaw events in most of the region. The number of thaw days in a given winter is a useful measure of winter severity in Labrador, as frequent or prolonged thawing of snow and ice cover is responsible for many negative outcomes for residents; e.g. melting snowmobile trails or failing sea ice cover present transportation hazards. To determine the expected number of thaw days, we employed a point process statistical model of thaw duration and frequency, which was used to estimate the number of thaw days expected in a season (Furrer et al., 2010). Figure 3.7 shows the likelihood of thaw events in Labrador, given as a return period or the typical length of time between events of this magnitude or greater. For example, the 100-year event is expected to be met or exceeded once a century, on average. Results show that the 2009/10 event in Labrador was very unusual in terms of thaw

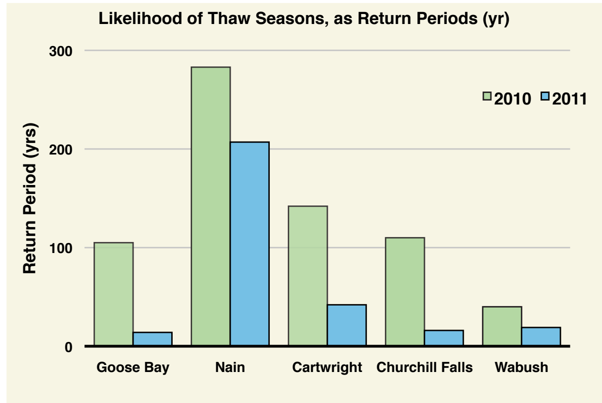


Figure 3.7. The likelihood of the number of thaw days observed in the winters (December–February) of 2009/10 and 2010/11 for five Labrador communities.

days, expected at most once every 100 years in 4 of 5 communities examined (Figure 3.7). The 2010/11 event was less severe, exceeding the 100-year event in only one location (Nain). These provide some context for these unusual winters; both were extremely unusual in Nain, but only the one was unusual in most of Labrador (becoming relatively common in western Labrador).

The timing of ice cover across Lake Melville demonstrates strong connections with climate. Figure 3.8 shows statistical test scores ('z' scores) for differences in mean ice break-up and freeze-up dates during the three Labrador climate regimes. Boxplots show the range of scores across the fourteen ice analysis locations, with one value calculated at each point (Figure 3.2). Comparisons to Regime 1 were not possible for freeze-up dates, as too few observations were available. Results demonstrate that no two regimes give universally significant differences in mean ice formation/break-up dates across all points. However, the most significant difference is seen between break-up dates in Regimes 1 (near-normal) and 3 (warm). Regimes 2 (cold) and 3 (warm) show similar, though weaker, changes. This is somewhat surprising and counter-intuitive; if climate were the only important driver, we would expect that Regime 2 as the coldest and 3 as the warmest would show the strongest difference. The inference is that some other non-climate factors are exerting an influence that further enhances differences between the mid-20th and early 21st century climates, and thus contribute to recent reductions in the length of the ice season. For example, gradual climate change may enhance differences between the early and late ice record; alternately, various non-climate factors (e.g. Churchill River discharge) may be impacting ice variability. However, it is also possible that these changes are an

continued on page 29

Box 3.1. **North Atlantic Oscillation**

The North Atlantic Oscillation (NAO) is a well-known (though still relatively poorly understood) atmospheric teleconnection pattern; that is, it represents a strong relationship between atmospheric conditions at locations separated by long distances. In the case of the NAO, this is a connection between the atmospheric pressure (or 'amount' of atmosphere) found in the subtropical and subpolar North Atlantic; this is commonly discussed as the relative strength of a subpolar Icelandic Low pressure system and corresponding subtropical Azores High. The NAO varies regularly (although somewhat unpredictably) between a 'positive' phase, during which these pressure systems are both unusually strong, and a 'negative' phase when they are unusually weak (or disappear entirely). These variations are related to the strength and position of the North Atlantic storm track, which typically carries the low-pressure systems responsible for cold season storms towards the Icelandic Low. A stronger-than-normal storm track will bring more (or stronger) low-pressure systems into the Icelandic Low, deepening this system; a weaker-than-normal storm track, or one displaced southwards, moves low pressures away from the Icelandic Low, weakening and/or displacing this system.

This change in the preferred path of storms exerts a strong influence on Labrador climate, particularly during the cold season. Its impact is illustrated in Figure 3.5, which shows the long-term mean atmospheric circulation (top panels), and conditions averaged over unusually warm periods in Labrador (bottom panels). In normal conditions, the Icelandic Low (marked with a bold red 'L') sits east of Greenland; it can be seen as an oblong blue 'low pressure' area in sea level pressure (SLP; right hand panels) and in the 1000 mb height contours. A piece of the low extends around the tip of Greenland into the Labrador Sea. This position encourages winds (shown as blue vectors in the left hand panels) to blow from the northwest along the Labrador coast and from the west in the Labrador interior, moving cold Arctic and subarctic air into the region. This set-up is promoted by flow aloft (500 mb heights, representing flow about 5 km above sea level; black lines in the right hand panels) in which southwest-to-northwest aligned contours indicate a strong and normally-situated Atlantic storm track. Unusually warm winter conditions are associated with a disruption in this pattern (bottom panels); the Icelandic Low is displaced eastwards, and no longer extends into the Labrador Sea. Winds over Labrador now flow from the south and west, blocking the entry of cold Arctic air. Upper level (500 mb) contours now suggest an easterly shift in the storm track, keeping the Icelandic Low away from the Labrador Sea. This 'Labrador-warm' circulation occurs more often during periods with a 'negative' NAO, but is rare during the NAO's positive or neutral (normal) phases.

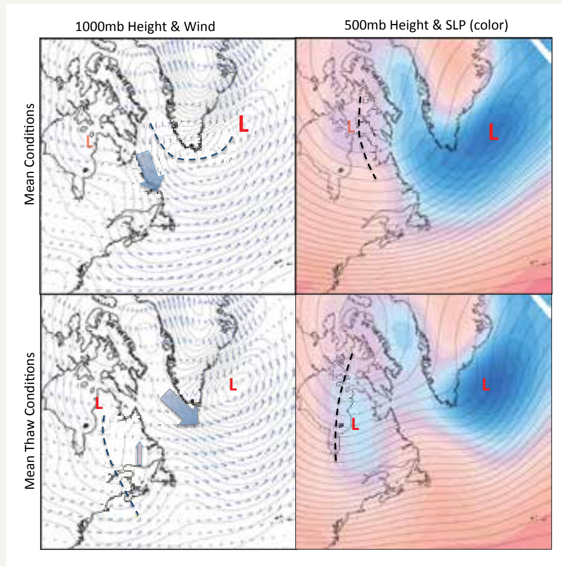


Figure 3.5. Winter atmospheric circulation under normal conditions (top panels) and during periods of strong, cross-Labrador winter thaws (bottom panels). Left hand panels show 1000 mb height contours, allowing low and high-pressure systems to be identified; near-surface (10 m) winds are also shown as blue arrows, the size of which indicates windspeed. Right hand panels show sea level pressure contours in color, with blue being low pressure; also shown are 500 mb height contours; winds at approximately 5 km altitude will blow parallel to these contours, maintaining a westerly component (e.g. south or north westerly following the contours). Also shown are the position of key surface low-pressure systems (given by a red 'L'), the orientation of important low pressure 'troughs' (dashed black lines), and dominant surface winds (large arrows on the left hand panels).

IN FOCUS

Box 3.2. **Atlantic Multidecal Oscillation**

The Atlantic Multidecal Oscillation (AMO) is a slow fluctuation in North Atlantic sea surface temperatures. The phase of the AMO is estimated by taking an average of these temperatures over the North Atlantic, removing long-term trends, and examining the signal that remains. These sea surface temperatures demonstrate a tendency to prefer 'above normal' or 'below normal' temperatures for long periods (years to decades). The reasons for these persistent anomalies is poorly understood, but is likely related to shifts in deep ocean circulation through the global ocean; deep water formed in the North Atlantic sinking, moving south at depth, and being replaced by warm surface waters flowing north. The AMO exerts an influence on Labrador by adjusting the transfer of heat from the warm ocean to cold overlying air throughout the cold season; the warm phase is consequently associated with warmer than normal Labrador temperatures.

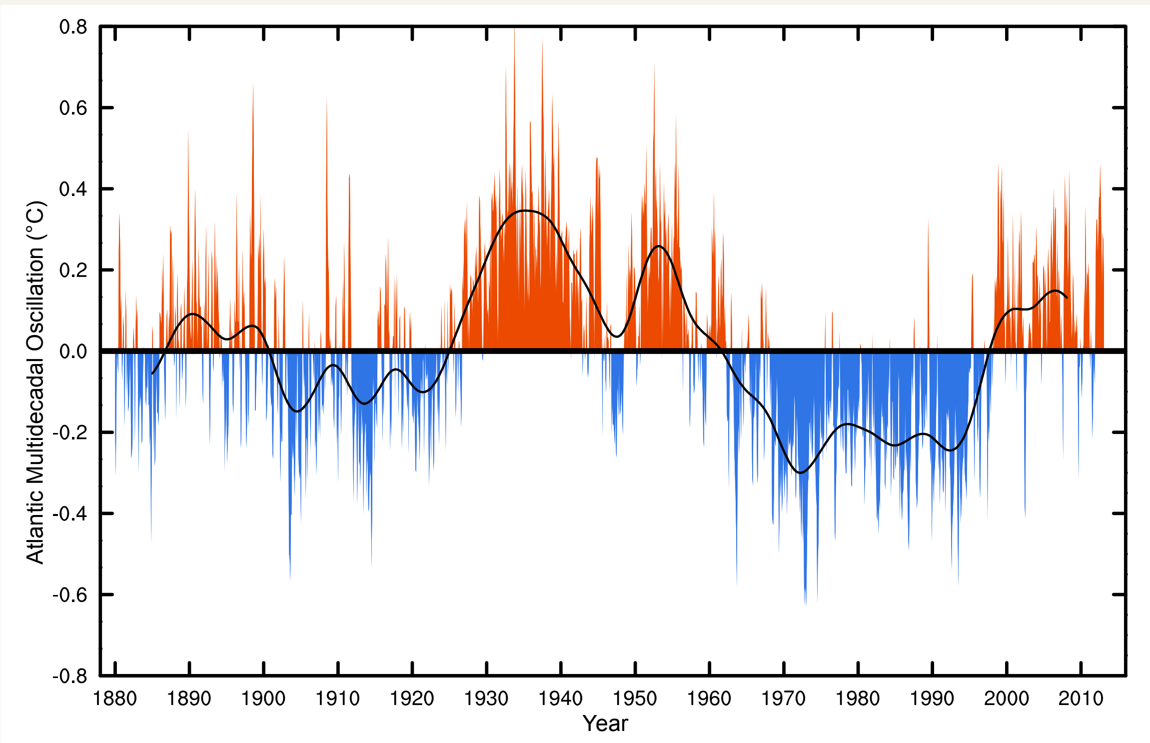


Figure 3.6. Shifts in the AMO over the past 135 years, as calculated following van Oldenbergh et al. (2009). Prolonged positive (warm) phases are shown in orange, while prolonged negative (cold) phases are shown in blue. Source: Giorgiogp2 (2012).

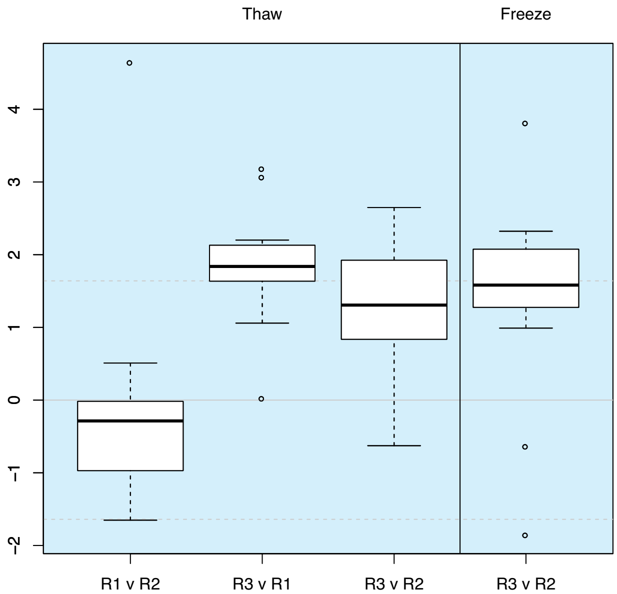


Figure 3.8. Statistical test scores ('z' scores) for the difference of mean ice break-up (thaw) and freeze-up (freeze) dates during the three Labrador climate regimes (see Table 3.1 for regime dates). Statistically significant differences lie outside the region between -1.64 and 1.64 (indicated by grey dashed lines).

artefact of the ice data used; over the study period ice charts have changed formats, the frequency of observation has increased from 7 to 5 days, and the instruments used to identify and characterize ice have improved.

Climate exerting greater influence on Lake Melville ice cover timing than Churchill River discharge

The strong influence of climate on ice cover on Lake Melville is also evident through the influence of temperature in preceding seasons on the timing of freeze up and break-up. With the notable exception of the Rigolet Narrows (portions of which remain ice free through much of the cold season), results show that anomalous freeze-up dates are strongly influenced by temperatures in the preceding fall, while anomalous break-up dates are influenced by temperatures in the preceding winter and spring (Figure 3.9, Figure 3.10).

The impact of Churchill River discharge on ice was also investigated. Flow through the river has the potential to influence ice cover through both mechanical disruption and influence on the salinity of the lake. Although there are some weak indications that Churchill River flow can impact the timing of ice cover, results demonstrate that the influence is much weaker than that of climate (Figure 3.9, Figure 3.10). However, it should not be inferred that discharge does not exert an influence, only that the impact of climate must be removed

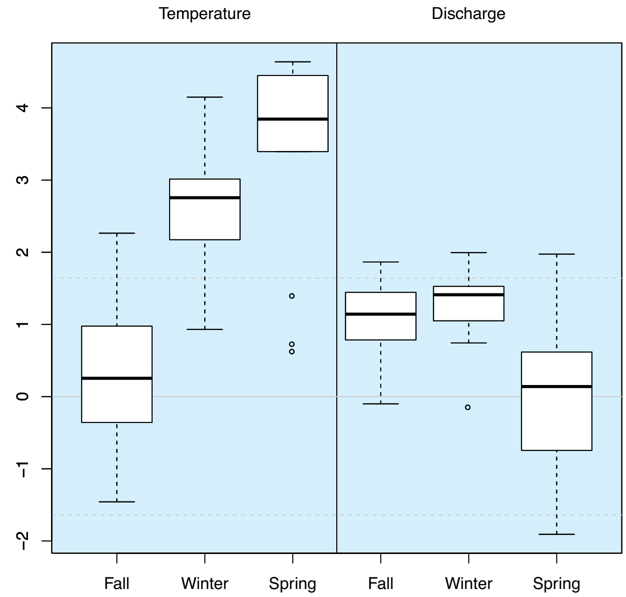


Figure 3.9: Statistical test scores ('z' scores) comparing seasonal mean temperature (as measured at the Goose Bay airport) and volume of Churchill River discharge for preceding seasons in relation to ice break up dates. Subsamples of the 20 earliest and 20 latest break-up dates at each of the 14 ice analysis locations were used. Significant results are found outside the delineated region between -1.64 and 1.64.

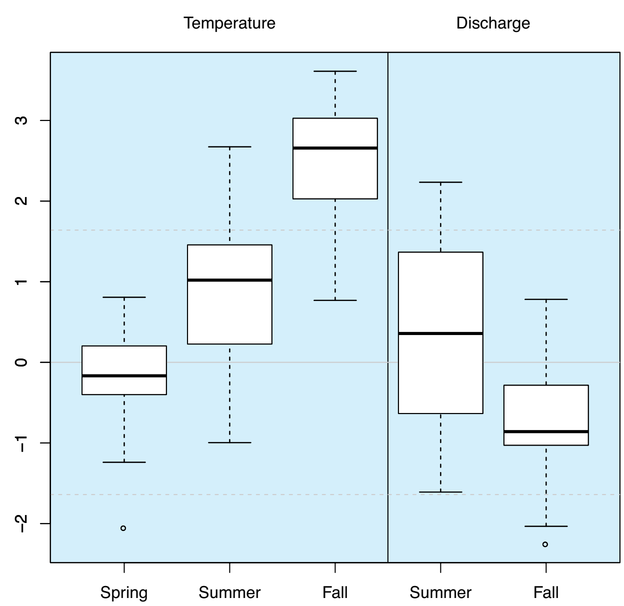


Figure 3.10. Statistical test scores ('z' scores) comparing seasonal mean temperature (as measured at the Goose Bay airport) and volume of Churchill River discharge for preceding seasons in relation to sea ice freeze up dates. See Figure 3.9 for additional information.

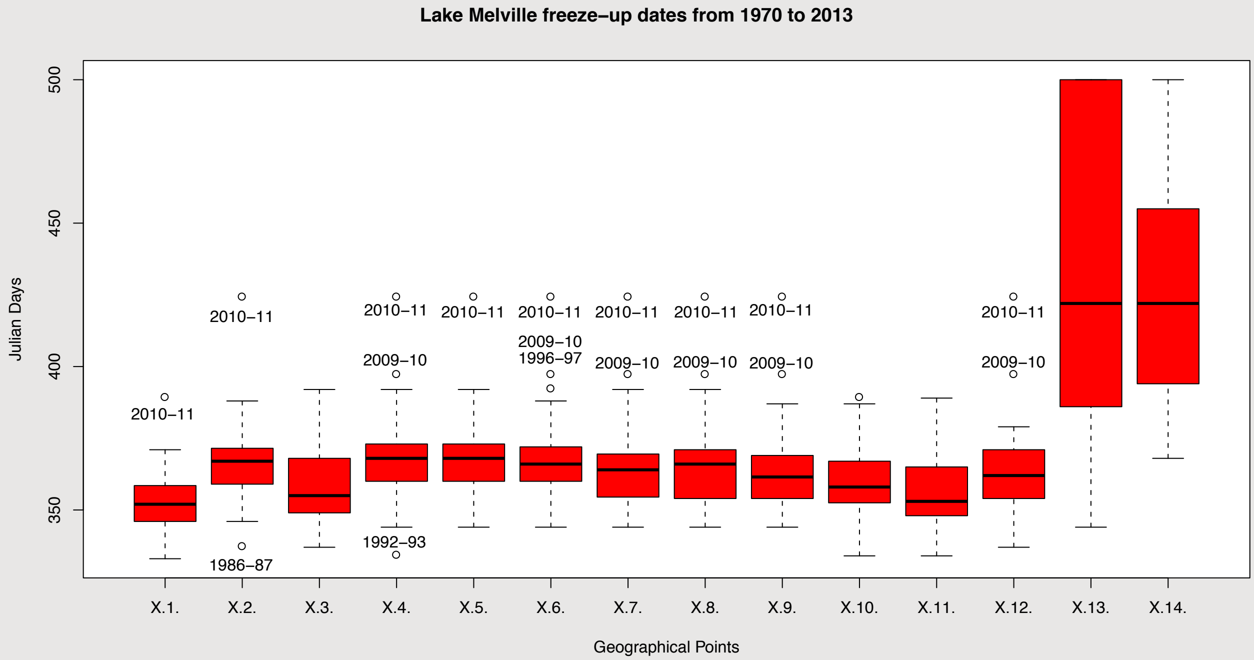


*Figure 3.11. Boxplots showing the range of first observed freeze-up dates (in Julian Day) for the fourteen points analysed on Lake **Melville.*** *Source: M. Smith, unpublished.*

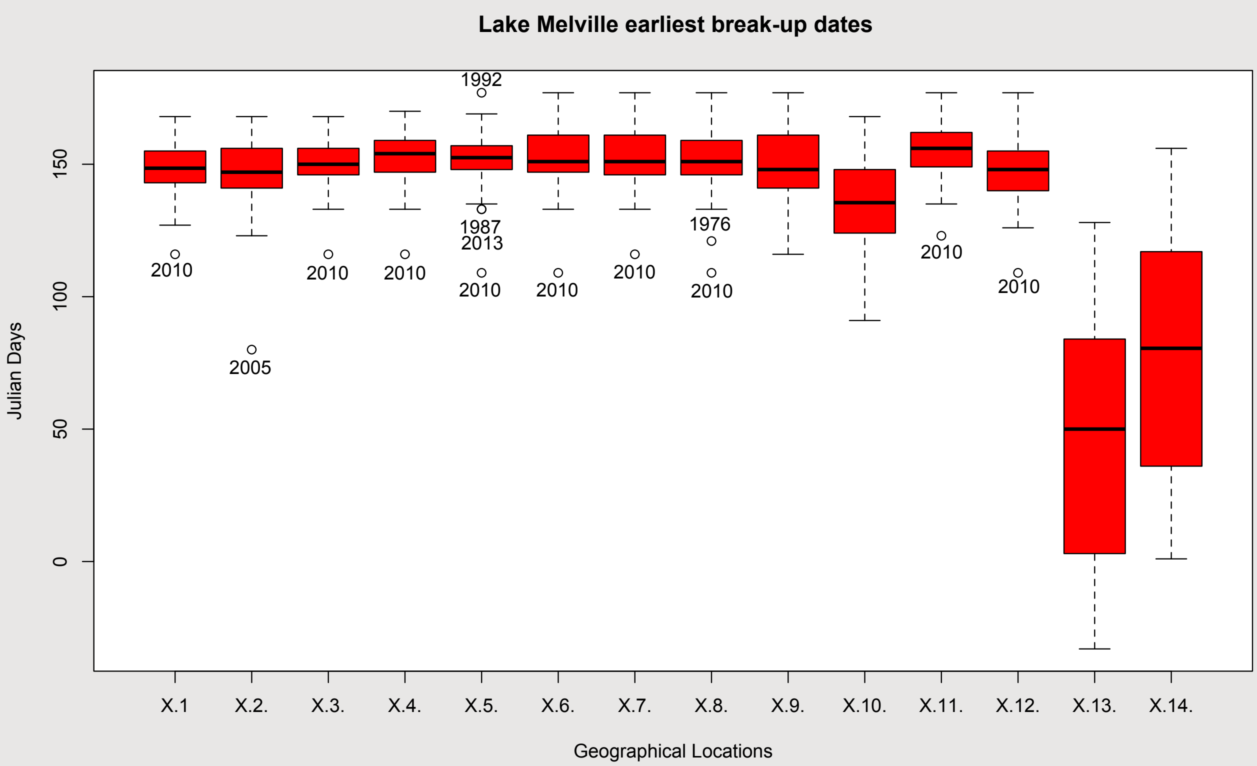


Figure 3.12. Boxplots showing the range of first observed break-up dates (in Julian Day) for the fourteen points analysed on Lake Melville.
Source: M. Smith, unpublished.

if discharge impacts are to be identified. Given the rough nature of the CIS ice data, resolving the impact of discharge may not be possible using observations alone. Future research could employ modelling exercises to estimate the relative capacity of climate and discharge to influence ice cover.

Variability in freeze-up and break-up dates in Lake Melville

The dates of ice freeze-up and break-up across Lake Melville vary considerably, with most locations demonstrating a range of 40 to 60 days (Fig. 3.11, 3.12). The exceptions are points 13 and 14, located in areas near the Rigolet Narrows that remain ice free through much of the winter. Prior statistical analysis indicates that a large portion of this variability is connected to climate; years with the earliest and latest break-up dates demonstrate significant differences in nearby temperatures during the preceding season (fall for freeze-up, spring and winter for thaw) (Figure 3.9, Figure 3.10; see Appendix 10.1 for additional data table).

Ignoring points near the Rigolet Narrows, the length of the continuous ice season varies from 77 to 189 days, with a mean of 150 days. Individual locations show standard deviations of two to three weeks; we can therefore expect anomalies of two to three weeks regularly (roughly two-thirds of all years), while anomalies of four weeks or great should be relatively rare (10% or less of all years). However, there is reason to believe that this is an overly generous estimate of natural ice season variability, inflated by a handful of recent events; the extremely unusual winters of the 2009/10 and 2010/11 produced large ice anomalies (77 ice covered days in several locations). Removing the influence of these large anomalies reduces standard deviations at most points down to 11 to 17 days. Given that the frequency of ice observation is approximately seven days, this is a matter of one to two observations on either side of the season. When these two anomalous winters are excluded, anomalies of three weeks or more become rare (<10% of observations).

Conclusions

Results provide some guidance for long-term ice use planning, as well as interpreting relative impacts of climate change and natural variability on human activity in the Lake Melville region. Climate change is occurring in Labrador, but emerging climate vulnerabilities (e.g. changes in the timing, duration, extent, and safety of ice travel) appear to be most strongly connected to climate variability (particularly the NAO). At present, the region is in the middle of a warm regime, under which extreme winter warming anomalies should be more common; this regime may persist for years to decades, impacting ice use and safety for some time. The relatively close timing of the shift between the neutral regime and the cold regime and the start of operations of the Upper Churchill development makes it difficult to fully separate the impacts of changes in climate from those of hydroelectric development on the timing of ice freeze-up and break-up in Lake Melville. There are some indications that non-climate factors, such as changes in Churchill River discharge, are enhancing differences between climatic influences in the neutral regime of the early 1950s to late 1970s compared to the warm regime of the late 1990s to early 2010s, but these observations could also be an artefact of the ice data used.

3.4. Potential future influences of climate on Lake Melville

Findings presented demonstrate that climate change is occurring in Labrador, but emerging climate vulnerabilities (e.g. changes in the timing, duration, extent, and safety of ice travel) appear to be most strongly connected to climate variability (particularly the NAO). At present, the region is in the middle of a warm regime. This regime may persist for years to decades, impacting ice use and safety for some time. As ongoing climate change progresses, it will gradually increase the chances of warm-regime related vulnerabilities. If trends continue, extreme winter warming anomalies, such as those observed during 2009/10 and 2010/11, may become more common under neutral regimes, as well as warm, and less dependent on the influence of the NAO and AMO. Consequently, if trends continue, the frequency of extreme winter anomalies where ice is increasingly hazardous or unusable is likely to increase, with impacts on the health and well-being of residents who rely on sea and freshwater ice for travel. At some point, a return to a cooler-than-normal climate regime may again obscure the impacts of ongoing change, but any such shift will be temporary.

Based on our analysis of the existing observational record, we were unable to fully separate the impacts of changes in river flow from climate impacts on the timing of ice formation and break-up in Lake Melville over the last several decades. As such, we are unable to project potential future impacts of any changes to river flow and temperature due to Muskrat Falls on ice formation and break-up timing in Lake Melville. Future changes depend on how hydroelectric development impacts on the river temperature regime interact with climate, and if climate impacts are linear or non-linear (e.g. if pre and post-development differences increase as air temperatures rise).

Community-based ice monitoring in blizzard conditions.

Credit: Rodd Laing

4. ICE MONITORING

Rodd Laing *Nunatsiavut Government*
Rob Briggs *C-CORE*
Trevor Bell *Memorial University of Newfoundland*

4.1. Introduction

The International Panel on Climate Change (2007) projected that the Labrador region will be among those with the largest and most rapid environmental changes driven by global climatic change of any region in the world. There have been observations of environmental changes in the Labrador region in recent years, including warmer temperatures, causing a decrease in extent and thickness of sea ice, permafrost thaw, increased coastal erosion, and changes in the distribution and abundance of key northern species, as well as increased variability and unpredictability in environmental conditions (Allard and Lemay, 2012; ACIA 2015; Lewkowicz and Harris, 2005; Wilson et al., 2014). Summer sea ice coverage along the Labrador Coast has decreased by 73% over a 40-year period, with sea ice decreasing an average of 1,536 km^2 per decade (Henry, 2011). Evidence presented in Chapter 3 indicates that climate change is occurring in Labrador, but that recent changes in the timing, duration, and extent of ice cover appear to be most strongly connected to natural climate variability. Nonetheless, any additional changes, whether development or climate driven, have the potential to enhance existing climate vulnerabilities.

Inuit in Labrador have observed and been directly impacted by these changes. Ice serves as critical infrastructure for Inuit. It is an important trail and access point to key travel and hunting areas around communities, and, in Labrador, facilitates access to wood for heating (Laidler et al., 2009; Nickels et al., 2006; Furgal and Sequin, 2006). This safe connection to land and sea is critical for Inuit health and well-being (Durkalec et al., 2014). Recent reports indicate that greater variability and unpredictability in ice and weather conditions and changes in the strength and stability of ice are contributing to increased travel and physical health risks for ice users (Durkalec et al., 2014; Furgal, 2008). Changing ice is less predictable (Aporta, 2011) and changes in the strength and quality of ice and timing of freeze-up and break-up make it more difficult to identify hazardous areas (Durkalec et al., 2014; Wolf et al., 2012). Changes in snow thickness also affect the safety and ease of travel; for example, reduced snow depth can cause damage to snowmobiles and equipment and increased accumulation can sink ice and obscure usually visible hazards (Pearce et al., 2012). Changes in ice and weather conditions also have the potential to limit access to important traditional food sources of Inuit, including fish and seals, with implications for food security.

Given the importance of ice for accessing food and travel, Inuit will continue to use ice and adapt as conditions change. Monitoring local ice and snow conditions at a scale that matters to ice users is essential for improving information available to them for managing travel risks. For example, ice users in Nunatsiavut have identified the need for increased information about ice and weather conditions to enhance community travel safety (Durkalec et al., in review). Local monitoring also contributes to the development of a long-term observational record of changes in the local ice regime. This project addressed a need to enhance community capacity to observe, track, and learn about changes in local ice conditions and to improve adaption to climate and environmental change and variability.

4.2. **Methods and approach**

We used two complementary approaches to better understand the ice system on Lake Melville and the surrounding area: 1) community-based ice monitoring stations and 2) a local remote-sensing system.

Community-based ice monitoring station

First, a community-based ice monitoring station was installed in 2014 in Lake Melville near North West River, on travel routes important to Inuit in the region (Fig. 4.1). When travel on ice was determined to be safe by a local Inuit ice expert, the station was installed using the method developed by Mahoney and Gearheard (2008) (Figure 4.2, Figure 4.3). At regular intervals (usually weekly), local ice experts measured snow depth and ice thickness using hot wires and stakes as

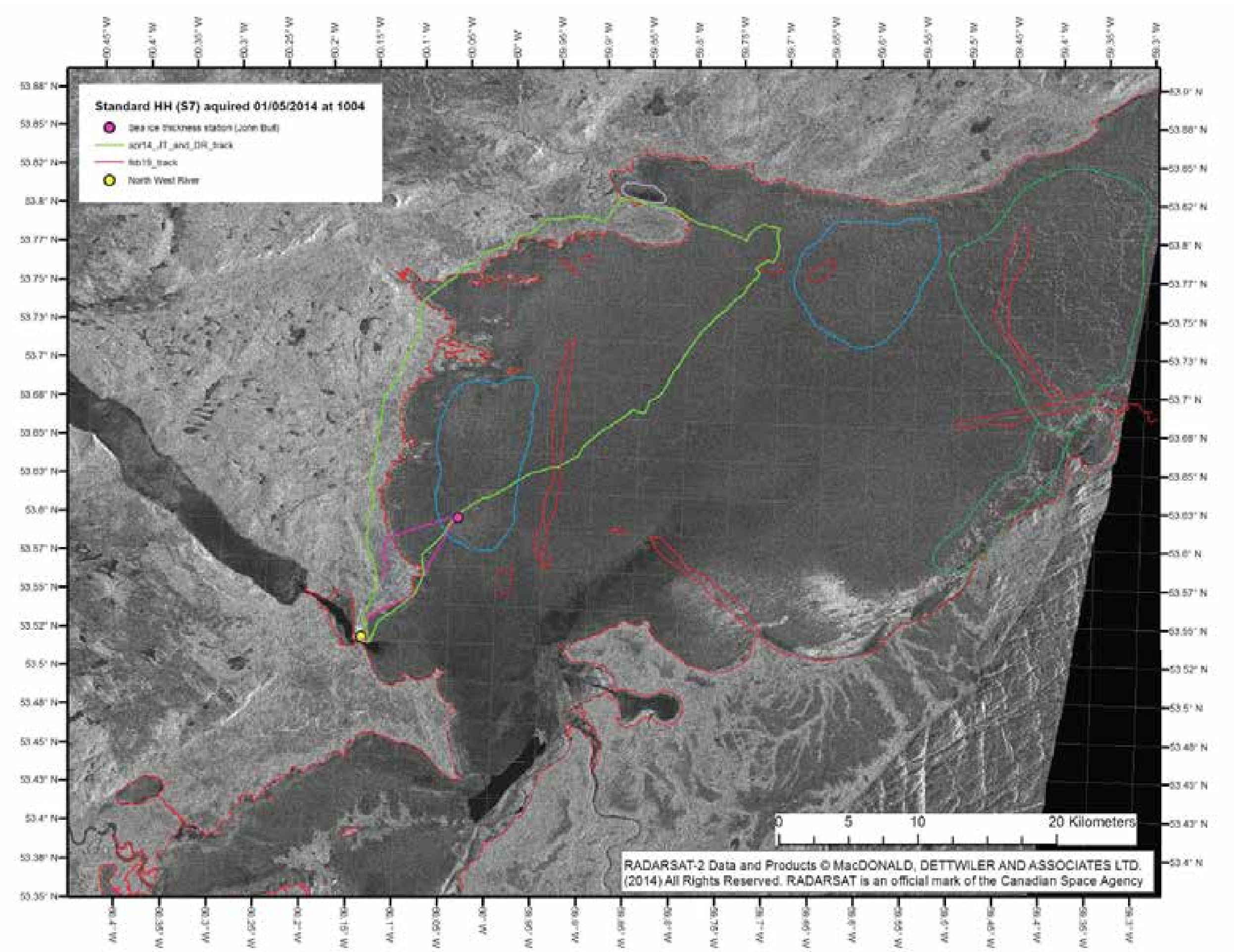


Figure 4.1. Annotated RADARSAT2 standard-mode image acquired over North West River in early May 2014 at the start of the break-up period showing the location of the ice monitoring station. The graticule, coastline, and legend were added prior to sending the image to the local ice expert (the light green and magenta lines represent Global Positioning Satellite (GPS) tracks of previous ground truth trips). The features identified and annotated by the local specialist are: cracks (red polygons), patches of snow with smooth ice in between (blue polygons), lines of rough ice with smoother ice in between (dark green polygons) and water on the ice (purple polygons). The local ice monitoring station and SmartICE buoy are marked with the pink dot. Synthetic Aperture Radar (SAR) data were provided through PolarView/C-CORE.

well as made any observations about the condition of the ice, travel routes and weather. These measurements and observations were then disseminated to local communities through social media, community bulletins and word of mouth and will be integrated into an online portal developed as part of the *SmartICE* (Sea-ice Monitoring And Real-Time Information for Coastal Environments) system (Bell et al., 2014).

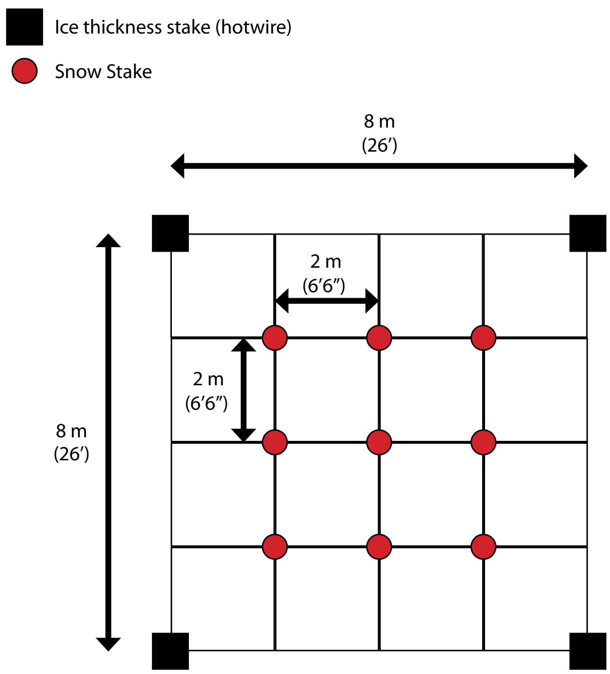


Figure 4.2. Layout of community-based ice monitoring stations. Source: Adapted from Mahoney and Gearheard (2008).

SmartICE local remote-sensing system

Second, Lake Melville is one of the sites that has been selected to prototype and develop the *SmartICE* system. This is a community-government-academic-industry collaboration that integrates *in situ* and remote sensing with a user specific terminology and knowledge (i.e. an ice classification system developed in conjunction with traditional Inuit knowledge). The main technology elements of the *SmartICE* information system are: 1) a network of *in situ* sensors that measures ice thickness at designated zones of interest and transmits daily data to a central server; 2) repeat satellite imagery over the region of interest from which ice surface conditions (e.g. concentration, roughness, water content) are identified and labeled following user-defined classification systems; and 3) information technology that integrates the *in situ* and remotely sensed data to generate raw and processed digital products that match the needs of user groups, such as Inuit ice experts, recreational ice users or ice navigation managers.

In situ SmartSENSORS. During the 2014/15 winter, a prototype ice thickness buoy called a SmartSENSOR was deployed alongside the community-based ice monitoring station in Lake Melville near North West River (Figure 4.4). The SmartSENSOR uses a chain of thermistors to measure a temperature profile through the ice and these data are transmitted daily by satellite to a central server. If there is a strong enough temperature gradient between the top and the

Figure 4.3. Installation of a community-based monitoring station.

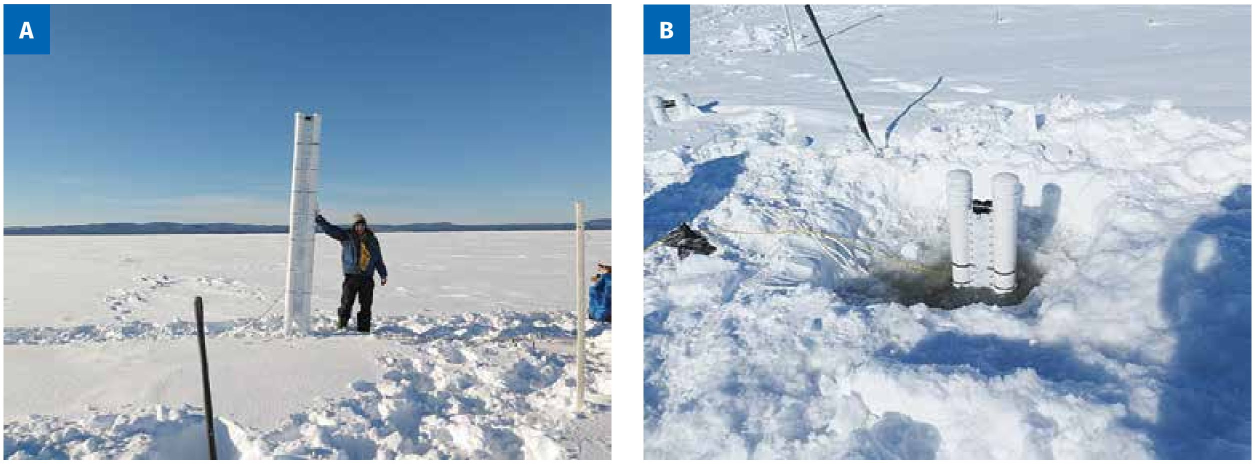


Figure 4.4. Photographs showing (a) the complete North West River SmartSENSOR with a researcher shown for scale and (b) the installation of the prototype through the ice near North West River.

bottom of the ice, then ice thickness (and snow depth) estimates can be made.

Satellite imagery and user-defined classification system. In addition to the installation of the SmartSENSOR, workshops were conducted with local ice experts who use and understand the Lake Melville ice regime. The workshops were used to identify common ice conditions (rough ice, smooth ice, rotten ice, open water) that the local ice expert deemed as important for making decisions about travel and navigation on the ice. The workshops also identified typical travel and hunting routes, areas of the ice that are typically unsafe for travel and avoided, and areas where the ice regime is poorly understood. Using this information, in conjunction with the data from the SmartSENSOR and community-based ice monitoring stations allows for the classification of ice at a local scale, including the identification of hazards and areas that should be avoided. Satellite images were provided to local ice experts to identify the different ice types and hazardous areas, which allowed for the production of images such as Figure 4.1. This ground-truthing exercise and local understanding are imperative for ice users, as large-scale ice charts and remote-sensing information does not capture the variability that exists in the Lake Melville ice regime at the scale used by ice users.

Information technology that integrates the in situ and remotely sensed data. An online portal is being developed to create a user-friendly, single point of access to the data associated with the *SmartICE* project. The portal will consist of maps, processed data and results showing ice thickness and temperature, and user-defined ice classification for local travel routes. The portal is not intended to replace traditional ice knowledge and observations, but to provide additional information to ice users at the appropriate scale to enhance ice-based travel decision-making in the context of increasing environmental variability and unpredictability.

4.3. Early results from a long-term ice monitoring program

In situ temperature monitoring indicates ice and snow thickness in Lake Melville

The SmartSENSOR was first deployed in Lake Melville in 2015, which allowed the device and sensors to be tested during a non-typical ice year (Figure 4.5). This resulted in improvements being made to the SmartSENSOR to ensure that the device will function in all conditions and for the entire duration of the ice season, from before freeze-up until waters are ice-free. Figure 4.5 presents a sample daily temperature profile that can be described in four sections: the vertical line at the top of the plot is the air temperature at around -20°C (white area), the upper sloped line from about -65 cm to -95 cm is the snow (green area), the second sloped line between -95 cm to -195 cm is the ice (blue area), and the lower vertical line is the ocean at a temperature of around -2°C (grey area). Using the temperature gradient, ice thickness and snow depth can be inferred at 100 cm and 30 cm respectively.

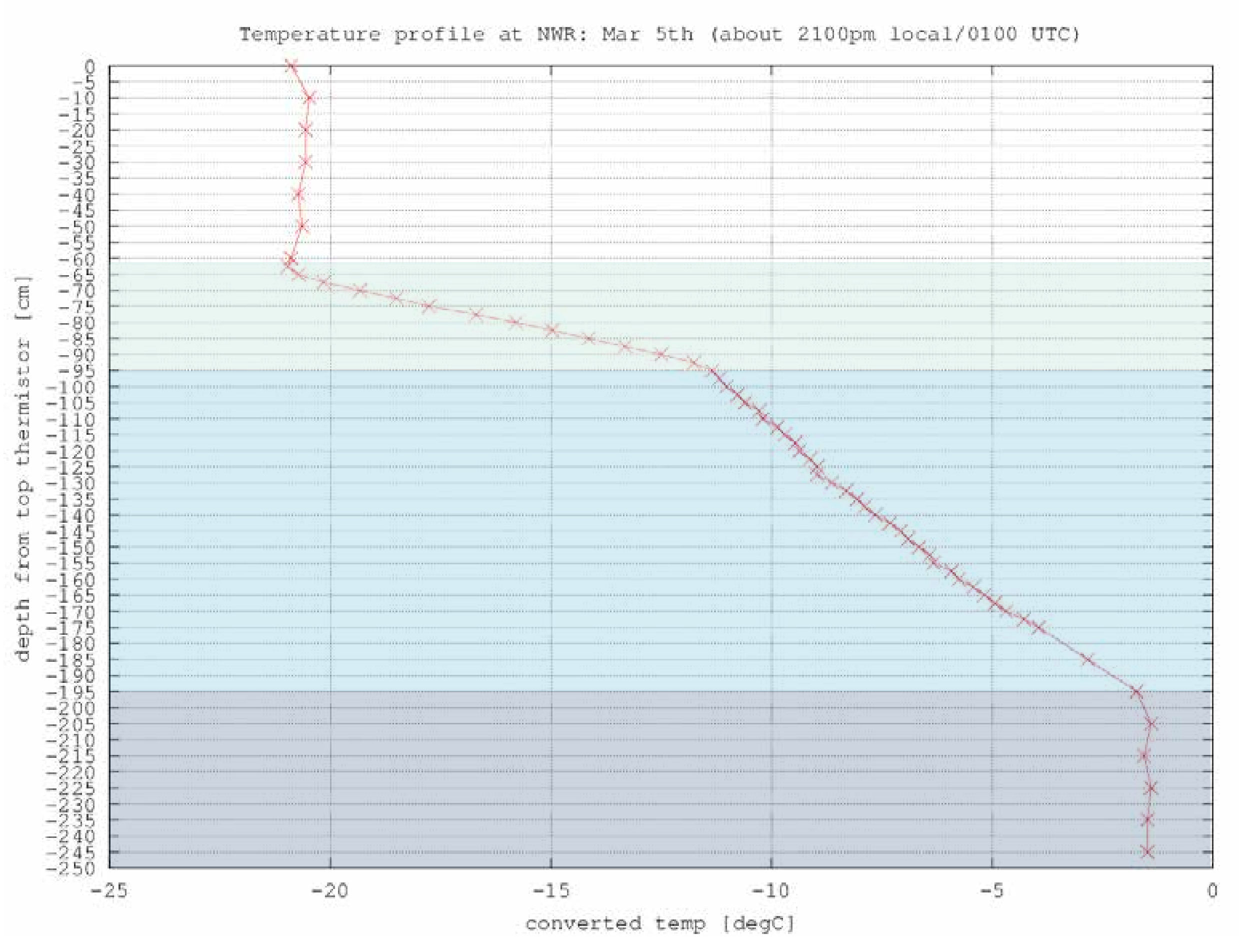


Figure 4.5. Temperature profile for the air (white), snow (green), ice (blue) and water (grey) at the North West River SmartSENSOR on March 5th, 2015. Using the temperature profile, the depth of snow (~30 cm) and thickness of the ice (~100 cm) can be inferred.

Community-based snow and ice monitoring shows high variability in snow and ice depths

Figure 4.6 shows the snow and ice depth during the sampling period of the community-based ice monitoring stations during 2014. Ice experts and local knowledge holders involved in the study indicate that the ice and snow depths are indicative of a typical winter on Lake Melville.

Figure 4.7 shows the snow and ice depth during the sampling period of the community-based ice monitoring stations during 2015. The ice experts and local knowledge holders involved in the study indicate that this winter was anomalous, with snow thickness being more than twice as deep as usual and ice being approximately 30 cm thinner than usual on Lake Melville.

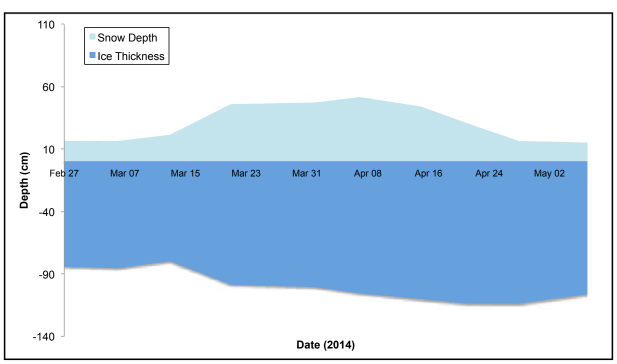


Figure 4.6. Snow and ice depth at the North West River community-based ice monitoring station during the 2014 monitoring period.

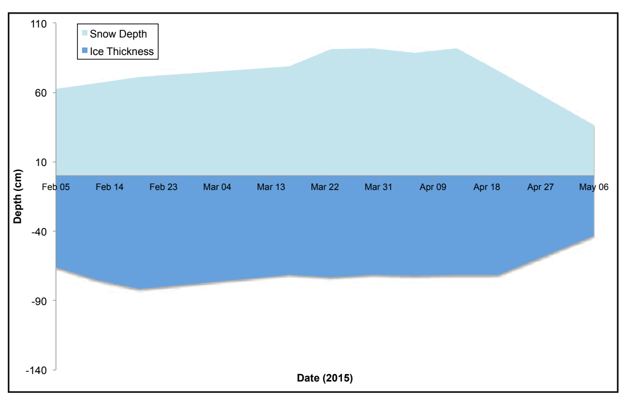


Figure 4.7. Snow and ice depth at the North West River community-based ice monitoring station during the 2015 monitoring period.

Table 4.1 presents the means and associated 95% confidence interval of the means for snow and ice depth for the 2014 and 2015 ice monitoring season of the community-based ice station. The difference between ice and snow depth in these two seasons is statistically significant (P<0.001), but needs to be approached with caution, as these are only two years of data.

Table 4.1. Comparison of snow and ice depth means at the North West River community-based ice monitoring station and the 95% confidence interval of those means for 2014 and 2015.

	Number of observations	*Mean (cm)*	*95% confidence interval (cm)*
Snow 2014	10	30.6	19.9 - 41.3
Ice 2014	10	99.9	90.9 - 108.9
Snow 2015	10	75.5	63.1 - 87.9
Ice 2015	10	69.7	62.5 - 76.9

The results for the two years of community-based monitoring show the inherent variability that exists between winters on Lake Melville. Winter 2014 consisted of average snowfall and ice thickness of approximately 100 cm whereas winter 2015 had more than twice the amount of settled snow on the ice and ice thickness of approximately 75 cm. The difference between years is likely due to the weight as well as the insulating factor of the increased snowfall during 2015, which also resulted in slushy conditions on Lake Melville and a quick break-up of the ice during spring. However, a quick break-up of the ice on Lake Melville is not unusual, as local ice experts identified that the ice can be relatively thick (~100cm) but break up due to strong winds or currents, which is what happened during spring of 2014. Using local knowledge and monitoring, in conjunction with *in situ* satellite devices, may lead to a better understanding of the spring ice regime of Lake Melville.

4.4 **Looking forward: The importance of ongoing monitoring**

There have been observations of changes in Labrador's environment in recent years, with reported changes in the distribution and extent of sea ice (Henry, 2011), an increase in the mean annual air temperature (Allard and Lemay, 2012), and changes in ocean temperatures (IPCC, 2007). Current models show a continued increase in air and ocean temperature in Labrador (Allard and Lemay, 2012 ; Finnis and Bell, 2015), which may decrease ice thickness as well as shorten the seasonal ice coverage of Lake Melville. A shortened ice-season with thinner and less predictable ice increases risks for Inuit that rely on the ice for harvesting and travel.

Furthermore, it is predicted that extreme weather events will increase related to the compounding effects of climate change and natural variability (Chapter 3; IPCC, 2012), which could have negative impacts on the ice regime of Lake Melville, especially during the freeze-up in late fall/early winter and during spring break-up. The strong winds, waves and currents associated with these extreme weather events could cause ice to shift, break up, increase the frequency of hazards, or create additional hazards that are not typically observed.

Inuit communities have also been reporting observations of increasing environmental change and variability (Furgal et al., 2002; Nickels et al., 2006). These changes include increasing unpredictability of weather and increase in the frequency and intensity of storm events. Air temperature has increased, the amount of snow has decreased and the sea ice season has become shorter (Furgal et al., 2002). These changes have resulted in increased exposure to health risks for Labrador Inuit who rely on the ice for activities such as travel to other communities, harvesting traditional food or gathering wood for household heating (Furgal, 2008).

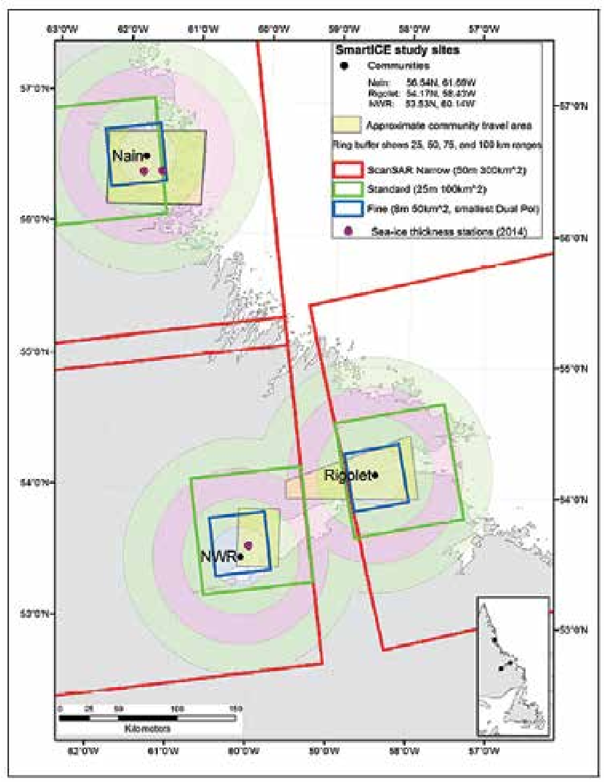


Figure 4.8. Map showing the locations of the SmartICE study communities, the approximate areas around the community that the local sea-ice users travel, a set of distance buffers centred on each community, and, to show how that satellite coverage relates to the community travel areas, the swath sizes for three of the RADARSAT2 sensors.

As additional information is collected from Inuit ice users, the community-based monitoring station and the *in situ* devices, our understanding of the Lake Melville ice regime will improve. Baseline data that are collected prior to the impoundment of the Muskrat Falls reservoir will be used to help differentiate climate-driven impacts on the ice and snow regime from downstream effects of the hydroelectric project. Furthermore, identical monitoring sites (ice stations and *in situ* devices) in Nain will be used as control sites to help differentiate between potential impacts of the hydroelectric project and observed changes in the climate (Figure 4.8). The Ice Formation Environmental Effects Monitoring Plan for the Lower Churchill project (Nalcor, 2014) is limited to monitoring effects of Muskrat Falls on the Mud Lake ice crossing on the Churchill River, near the river mouth, and does not include surveying ice conditions in Lake Melville.

The collection of these data is expected to lead to a better understanding of the Lake Melville ice regime, which can help Inuit adapt and mitigate the effects of changes in the ice and weather. This adaptation can be through increased monitoring and production of maps of known areas of ice that are either unpredictable or unsafe during some or all of the ice season. The greatest risk for Inuit health and well-being is during the shoulder ice seasons (freeze-up and break-up), where travel and ice conditions can be difficult and limited data are available. The *in situ* SmartSENSORS are expected to provide critical information during these time periods. This information, augmented with local knowledge and community-based monitoring, will provide valuable observations of changes in the ice regime and help Inuit adapt to any impacts of these changes.

Deploying the box corer to retrieve sediments from the Lake Melville seafloor.

Credit: Rodd Laing

5. SEDIMENT AND ORGANIC CARBON

Michelle Kamula and Zou Zou Kuzyk *University of Manitoba*

5.1. Introduction

Reservoirs created as a result of hydroelectric projects are known to disrupt the fluxes, or flows, of materials from land to downstream environments. These materials include sediment, particulate (large-sized) organic matter and carbon, contaminants and nutrients, and are important in biogeochemical cycles, supporting food webs, and various other processes in the downstream environments (Friedl and Wüest, 2002; Humborg et al., 1997; Syvitski and Kettner, 2011). Estuaries, where rivers discharge into the sea, are sometimes the ultimate downstream environment, where the consequences of these altered fluxes manifest. These changes may then be seen in an altered balance of land-derived vs. marine inputs and sedimentation or burial of organic materials, or altered supply of organic carbon to the base of the food web.

In the context of the proposed development of a hydroelectric dam and reservoir at Muskrat Falls on the lower Churchill River, this project set out to establish baseline conditions related to the fluxes of materials, especially sediments and carbon, from the Churchill River into Lake Melville, and their importance relative to other inputs; to assess the fate of these materials in the Lake Melville system; and to seek insight into the potential consequences of changes to these fluxes resulting from the proposed development. The focus was on sediment and organic carbon because sediment provides a means of burying both carbon and contaminants of concern such as mercury, while organic carbon is at the core of biogeochemical cycling for almost all other elements (e.g. nitrogen, phosphorous), and essentially supports the base of the food web.

A central component of our research focused on collecting, analyzing and interpreting sediment cores. Sediment that gets deposited and remains undisturbed on the bottom contains a record of the environment from which it was sourced and the conditions under which it was deposited. Thus, the sedimentary record provides a means of understanding the sources of sediment and organic carbon to the system and the processes affecting it (metabolism, resuspension) after introduction. It was also anticipated that we would find a record of historical organic carbon composition and burial in the estuary, in which we could seek evidence of impacts from past developments on the Churchill River that could inform our understanding of the system's responses to change and predictions of future impacts.

Figure 5.1. The box core used to retrieve sediment from the seafloor.

Figure 5.2. Sub-sampling of retrieved sediment using a push tube.

This study is the first to describe modern sediment and organic carbon sources, fluxes and distribution in Lake Melville. Previous work on sediments and organic carbon was conducted with a view to long-term paleoenvironmental reconstructions (approximately 10,000 years) (Tan and Vilks, 1987). Modern sedimentation rates, organic carbon sources and burial patterns have not been assessed, despite the importance of these data as a baseline for assessing the impacts of future development or climate change (Macdonald et al., 2015). Sediment and organic carbon fluxes are also essential for calculating budgets (i.e. accounts of the sources (flows in) and sinks (flows out)) of contaminants (Hare et al., 2008; Johannessen et al., 2005) and for gaining insight into food web structure and productivity of a system (Kuzyk et al., 2009). Impacts of past hydroelectric development (Bobbitt and Akenhead, 1982) and recent climate change are also virtually unknown.

5.2. **Methods and approach**

Sediment cores and water samples were collected from various depths at 14 sites across Lake Melville in June 2013 and October 2014 aboard the R/V *Nuliajuk* (2013) and M/V *What's Happening* (2014). Sediment cores were collected across Goose Bay and Lake Melville to reconstruct the modern sedimentary record (i.e. cores of 10–30 cm in length, representing sediment deposited during approximately the last 100–150 years). We employed a box core for sediment core collection, which is designed to penetrate the sea floor and then close, sealing in undisturbed sediment and overlying water (Figure 5.1). Successful box cores (i.e. water tight seal and/or undisturbed sediment) were sub-sampled by carefully pushing a tube into the sediment and capping it at both ends (Figure 5.2). While aboard, sediment cores were sectioned (top to bottom) into 1 cm intervals, and the sections were placed in bags and stored frozen until later analysis. Surface water from across the lake and major rivers (Churchill, Goose, and Northwest Rivers) was also collected for analysis of salinity, nutrients, total suspended solids, particulate organic carbon, and stable isotope ratios of carbon ($\delta^{13}C$), which provide a proxy for assessing the composition of the organic carbon.

At the University of Manitoba in Winnipeg, sediment sections were freeze-dried, ground, and analyzed for radioisotopes lead-210, radium-226, and cesium-137 (^{210}Pb, ^{226}Ra, ^{137}Cs, respectively). These radioisotopes bind to particles, becoming incorporated into the

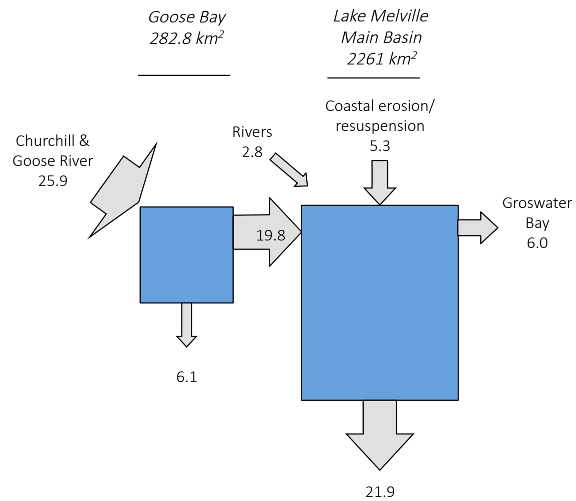


Figure 5.3. Mass balance budgets of sediment (x10^8 kg yr^{-1}). Arrows pointing towards a box represent inputs and arrows pointing downwards represent sinks.

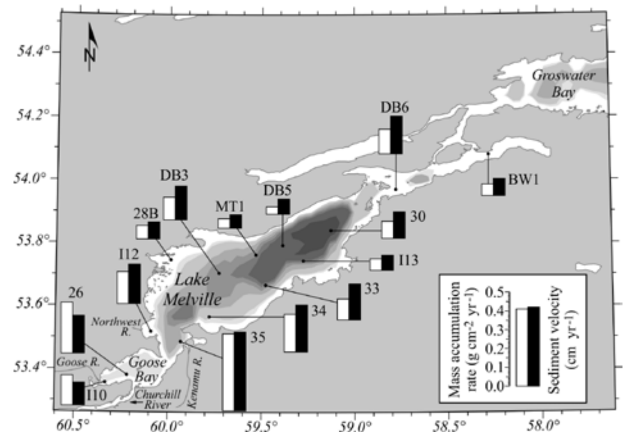


Figure 5.4. Sediment velocity (cm y^{-1}) and mass accumulation rates (g cm^{-2} y^{-1}) across Lake Melville determined from radioisotopes $^{210}Pb_{ex}$ and ^{137}Cs activities down sediment cores. Core names are shown on top or beside bars.

sedimentary record where they decay at a known rate (see Kuzyk, 2015). The radioisotope data measured in sediment cores were then used to develop sedimentation rates across Lake Melville and to infer major sedimentary processes within the system.

Organic carbon content and $\delta^{13}C$ were also measured on selected sediment sections (surface sections and selected cores). The organic carbon content was used together with sedimentation rates in the cores to estimate the fluxes, metabolic losses, and burial of organic carbon in the system. The $\delta^{13}C$ data were used to apportion the total organic carbon content into marine- and terrestrial-type organic carbon (Johannessen et al., 2003). Finally, the newly acquired data on rates of sedimentation, terrestrial and marine carbon supply, metabolism, and burial were used together with previously published data to construct preliminary baseline sediment and organic carbon budgets for the system. Full details of methods are available in Kamula (2015).

5.3. **Understanding the sediment and organic carbon cycle of Lake Melville**

Churchill River is the greatest source of sediment to Lake Melville

Sediment supply by the Churchill River and other major rivers was estimated from newly collected and previously published total suspended solids (TSS) and river discharge data. The results indicate that the Churchill River is the single largest source of sediment to the Lake Melville system supplying 25.2 x 10^8 kg yr^{-1} or 74% of total sediment inputs to Lake Melville. Our calculations show that under present conditions the majority (19.8 x 10^8 kg yr^{-1} or 78%) of the Churchill River's TSS load is carried beyond Goose Bay and into Lake Melville (Figure 5.3).

Sediment accumulation rates are generally greatest in the western end of the lake and decrease eastward with distance from the mouth of the Churchill River (Figure 5.4). Averaging the accumulation rates over the various basin areas, about 6.0 x 10^8 kg yr^{-1} or 21% of the sediment supplied by the Churchill River is trapped in Goose Bay, while the remainder is transported eastward into Lake Melville proper. This sediment supply then supports a strong sediment sink in a series of troughs and basins in the western end of the main basin, east of Goose Bay. A secondary factor influencing sediment distribution is sediment input from other rivers, particularly the Kenamu and Northwest Rivers.

Strong gradient of terrestrial to marine organic carbon in sediments from west to east

Based on measurements of the particulate organic carbon (POC) content of river water from the Churchill, Goose and Northwest Rivers, the Churchill River represents the most important source of terrestrial organic carbon to the Lake Melville system. Our calculations show that the Churchill River supplies 62% (18.4 x10^6 kg yr^{-1}) of terrestrial POC to the downstream estuary with about 17.6 x10^6 kg yr^{-1} presumed to be transported with surface water through Goose Bay

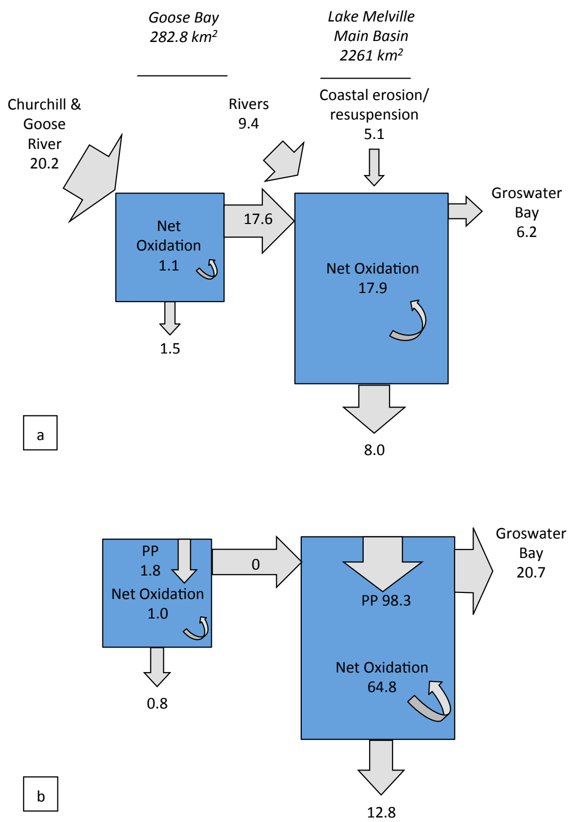


Figure 5.5. Mass balance budgets of (a) terrestrial POC (x10^6 kg yr^{-1}) and (b) marine POC (x10^6 kg yr^{-1}). Arrows pointing towards a box represent inputs, arrows pointing downwards represent sinks, curved arrows represent net losses by oxidation and PP is primary production.

Narrows to Lake Melville (Figure 5.5a). We presume the export of POC parallels suspended sediment exports to Groswater Bay (i.e. 21% of river inputs). Based on this assumption, we calculated a loss of terrestrial POC to Groswater Bay and the Labrador Sea of 6.2 x 10^6 kg yr^{-1}.

The total organic carbon (TOC) content of the sediments across the lake is generally quite low, varying from 0.5%–1.0% in the western part of the lake near the rivers to 1.0%–1.5% in the eastern end of the lake (Figure 5.6). The contribution of terrestrial organic carbon to this sedimentary TOC is estimated using the stable carbon isotope ratios ($\delta^{13}C$), which are very low in the terrestrial organic carbon that enters the system (~ -31‰), compared to the values in marine organic carbon sources (~ -21‰). The $\delta^{13}C$ values in the Lake Melville sediments vary from about -28‰ in Goose Bay, -27.5‰ in western Lake Melville (Epinette Basin), -24‰ in eastern Lake Melville near the Rigolet Narrows, and -22‰ in Groswater Bay, east of the Rigolet Narrows. From the relatively low values throughout Lake Melville, compared to Groswater Bay, it may be inferred that terrestrial organic carbon is transported all across the lake as far as the Rigolet Narrows. This wide distribution of terrestrial organic carbon presumably occurs in association with the eastward flow of surface waters, driven by freshwater input. The increasing $\delta^{13}C$ values from west to east in part reflect diminishing influence of terrestrial organic carbon eastward. However, the trend also reflects increasing marine supply toward the eastern end of the system, as indicated by greater sedimentary organic carbon content (Figure 5.6) and greater inventories of ^{210}Pb, which reflect this tracer being pulled out of the water column and transported to the seafloor with settling particles (Figure 5.7; see Appendix 10.2 for additional supporting data). Based on the $\delta^{13}C$ proxy, marine organic carbon contributes more than 50% to sedimentary organic carbon in the eastern end of the system, compared to <25% marine-derived organic carbon closer to the river mouths.

In terms of the biological oceanography and ecosystem structure, we hypothesize that marine organic carbon (i.e. algal production) may be more significant in the eastern part of the system because of clearer surface waters (fine grained terrestrial particles having settled out) and greater nutrient replenishment through marine inflow and/or upwelling of nutrient-rich deep waters. Rates of primary production determined from the marine fraction of organic carbon in the sedimentary record suggest productivity in Lake Melville (98.3 x 10^6 yr^{-1}) is an order of magnitude greater than in Goose Bay (1.8 x 10^6 yr^{-1}) (Figure 5.5b). Because conditions for primary production are relatively poor throughout much of the Lake Melville system (low surface water clarity, short surface water residence time), terrestrial organic carbon may be an important source of metabolic energy supporting the food web. Although we do not know the specifics of energy transfer in this system, based on results from other river-dominated systems such as the Mackenzie Delta, we would expect a planktonic bacterial community supported by terrestrial organic carbon to exist in Goose Bay and the western end of the main Lake Melville basin, within the terrestrial organic carbon-rich plume of the Churchill River. Within the sediments, a benthic bacterial community supported in part by terrestrial organic carbon may exist all across Lake Melville.

Increase in terrestrial organic carbon ratio in Lake Melville shows sensitivity to river changes

The balance of terrestrial vs. marine organic carbon in Lake Melville sediments appears to be sensitive to changes in the supply of terrestrial materials, as may be expected from climate change or hydroelectric development. In the sedimentary record of the last few decades, we find a significant shift in the $\delta^{13}C$ proxy upcore, which suggests an increase in terrestrial organic carbon inputs (Figure 5.8). In Figure 5.7, cores that lay to the right of the line reveal an increase in ^{137}Cs sourced from the terrestrial environment while cores that fall to the left of the line suggest additional inputs of $^{210}Pb_{ex}$ from seawater. Possible explanations include increased river flows, flooding of land, or forest fires/clear cut logging in the watershed. The shift is particularly pronounced in central Lake Melville, where it appears that marine organic carbon was once equally or more important than terrestrial organic carbon but now terrestrial organic carbon is the dominant source. With shifts in the balance of terrestrial vs. marine organic carbon, there would likely be shifts in the intensity of metabolism in the system (reflecting terrestrial organic carbon being less metabolizable), and in food web structure (favouring microbial systems, for example). Findings suggest that central Lake Melville is sensitive and responsive to changes in rivers and/or their watersheds, despite being quite removed from the actual river mouths.

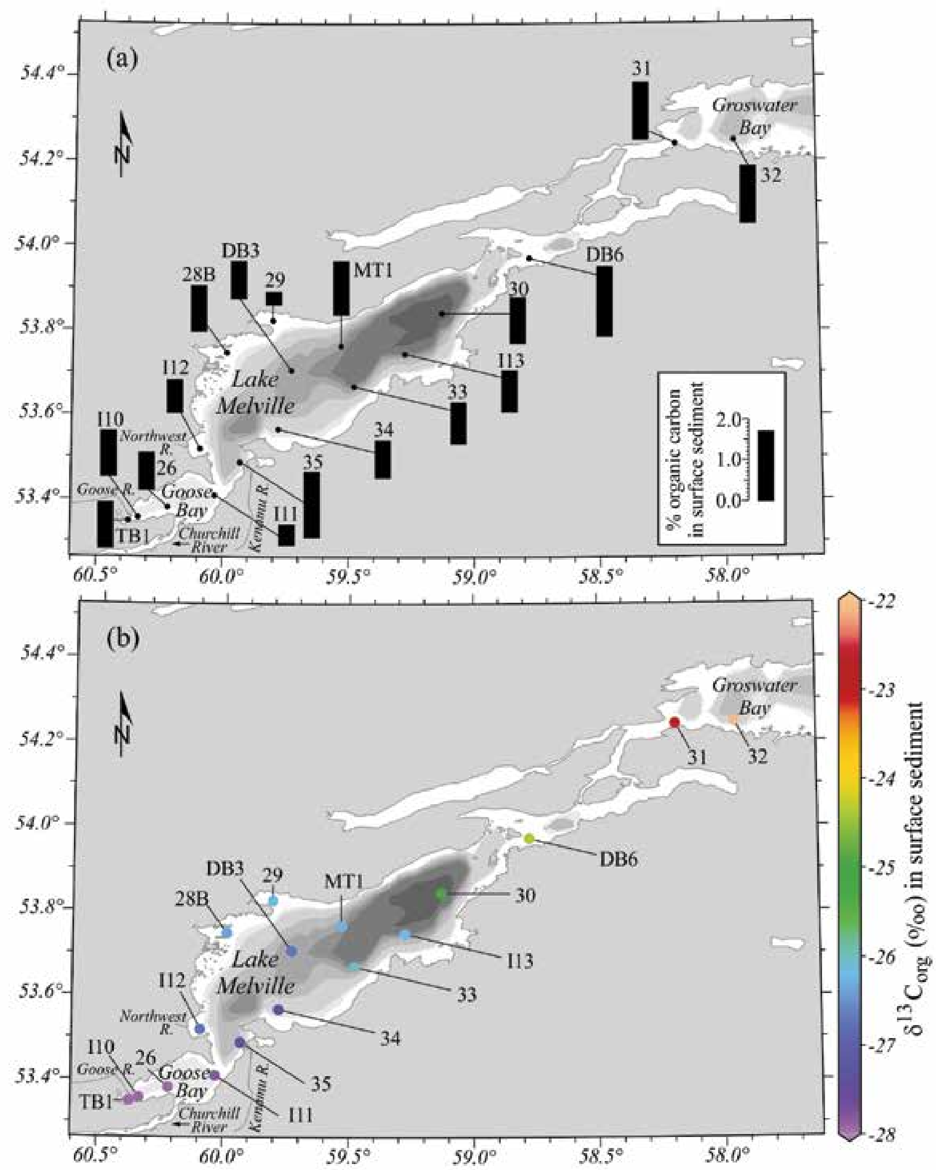


Figure 5.6. (a) Organic carbon (%), and (b) $\delta^{13}C_{org}$ (‰) in surface sediment across Hamilton Inlet.

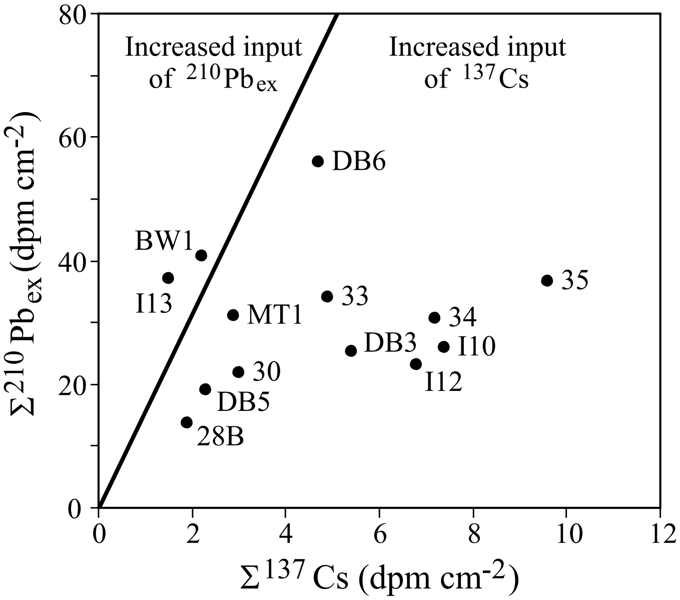


Figure 5.7. Excess ^{210}Pb ($^{210}Pb_{ex}$) and ^{137}Cs inventories and their ratios in sediment cores compared to the expected inventories from direct atmospheric fallout (straight line).

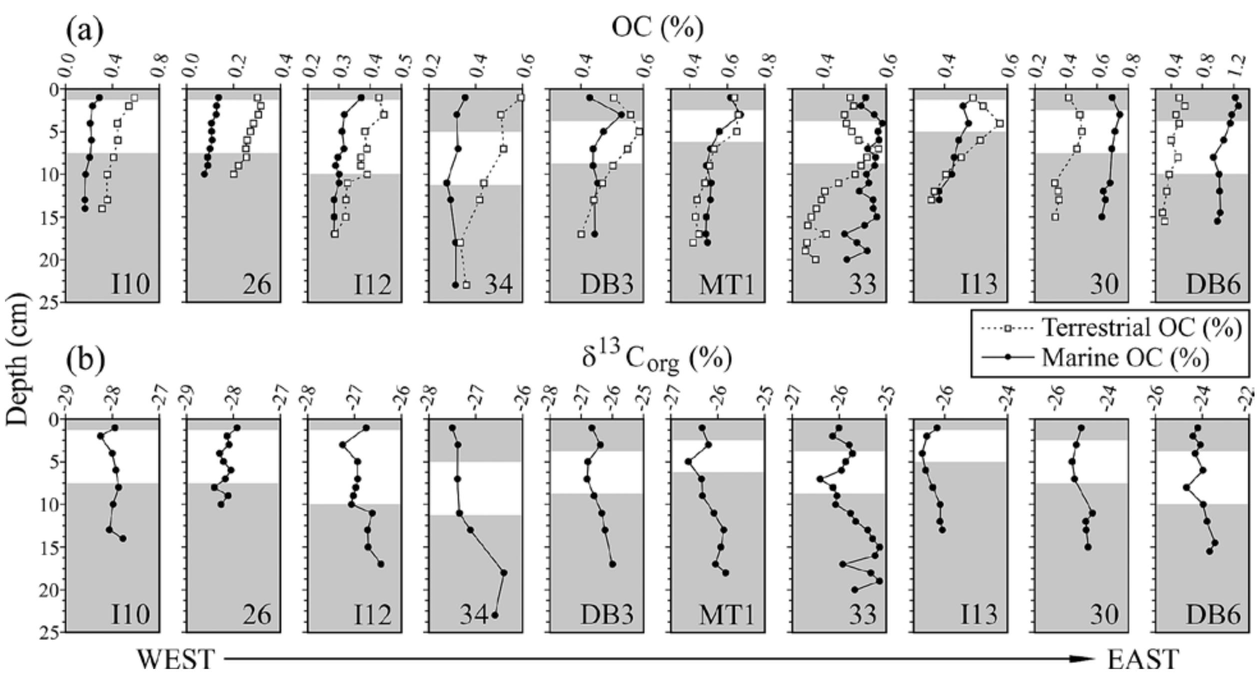


Figure 5.8. Downcore profiles the percent contribution of (a) terrestrial and marine organic carbon (OC) and (b) δ13C. The shaded area represents sediment deposited before (bottom) and after (top) 1970.

Conclusions

First, mass accumulation rates established from sediment core geochronology show the greatest accumulation of sediment in western part of the main Lake Melville basin, on the east side of Goose Bay. In this location, TOC in surface sediment was three times greater than at a nearby core site in Goose Bay. This indicates that sediment is being carried in suspension eastward in the surface waters of the large Churchill River plume through Goose Bay Narrows where currents are fast and flow direction is consistently eastward (seaward) during both ebb and flood tide. The effects of strong currents on sediment deposition (i.e. mixing and resuspension) are reflected in both the low and homogenised radioisotope profiles and exceptionally low total organic carbon in surface sediment on the westward side of Goose Bay Narrows.

Second, although quite removed from the river mouths, sediment core analysis in the western end of the main Lake Melville basin revealed a small but significant increase in terrestrial organic carbon over the last four decades. It is likely that the Churchill River, as the strongest source of terrestrial organic carbon to Lake Melville, contributed to this increase. Specifically, changes in the flow and drainage area of the Churchill River caused by the Upper Churchill hydro development starting in the 1970s could have released terrestrial organic matter as has been documented for other hydro developments (Houel et al., 2006), thus likely increasing the delivery of POC to Lake Melville, at least for some period until the system readjusted (Newbury and McCullough, 1984).

Our results show that most of Lake Melville is strongly influenced by the sediment and organic carbon delivered by Churchill River inflow, demonstrating a strong relationship between this river and lake. Algal production appears to increase in the eastern end of the lake but otherwise the supply of organic matter from the river may represent the main support at the base of the food web. Based on sedimentary records, there has been a significant increase in supply of terrestrial organic carbon to Lake Melville post 1970, which we interpret as most likely reflecting both change in climate and hydrology of the Churchill River.

5.4. Future changes to sediment and organic carbon inputs to Lake Melville

With the Churchill River providing by far the most important sediment source for Lake Melville, perturbations to the sediment supply from the Churchill River due to climate change or Muskrat Falls development will likely impact overall sedimentation, including the capacity to bury substances (carbon, contaminants) in Lake Melville. The sites of sediment accumulation and carbon/contaminant burial will also be altered, with a decrease in the relative importance of Goose Bay and increase in western Lake Melville proper (where other rivers supply sediments). The newly acquired data on sedimentation rates provide a baseline for assessing these future impacts. With changes in the seasonality of river flow having an influence on salinity, ice transport, and ice volumes in specific areas of the lake (see Chapter 2), indirect effects on algal production and hence carbon cycling and the base of food web may be expected.

The Churchill River is the largest source of sediment and terrestrial POC to Goose Bay and Lake Melville delivering 25.2 x 10^8 kg of sediment yr^{-1} and 18.4 x10^6 kg POC yr^{-1} to the downstream estuary. Of this, 74% and 62% of the rivers suspended sediment load and terrestrial POC is carried beyond Goose Bay and into Lake Melville proper. To investigate the potential changes to the sediment and terrestrial organic matter input from the Churchill River to the downstream estuary following impoundment at Muskrat Falls, we applied the median reservoir shoreline erosion potential of 5.25 m yr^{-1} per metre of shoreline reported by Amec (2008) and, following the author's assumptions, we assumed a 10 m bank height. Applying these values to the proposed approximate reservoir shoreline of 35.5 km and assumed bulk density of 2,600 kg m^{-3} and assuming half the eroded soil and organic matter remains trapped in the reservoir and sand bars downstream, our calculations showed that the suspended sediment and terrestrial POC load of the Churchill River to the downstream estuary could potentially double to 49.5 x 10^8 kg sediment yr^{-1} and 24.3 x 10^6 kg terrestrial POC yr^{-1}. It is expected, as observed in previous impounded systems (see Newbury et al., 1984), that once the shoreline readjusts to the new water levels the particulate load of the Churchill River will decrease. However, this decrease to baseline conditions could occur over a longer, unknown, timescale – potentially decades (see AMEC, 2008).


A fishing boat on Lake Melville.

Credit: Ashlee Cunsolo-Willox

6. METHYLMERCURY

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6.1. Introduction

Methylmercury is a potent neurotoxin that has been associated with a variety of adverse health effects on humans. At high levels of exposure it is a central nervous system toxin causing kidney and liver failure. Early signs of acute methylmercury poisoning include tremors, dizziness, memory loss, hair loss, blurred vision and tingling at the extremities (Clarkson et al., 2003). Chronic low levels of exposure are typically observed among frequent seafood consumers. Long-term dietary exposure to methylmercury has been associated with neurocognitive delays in children including long-term IQ deficits, attention deficit behavior and reductions in verbal function and memory. For example, prenatal methylmercury exposure has been linked to attention deficit symptoms in school-age Inuit children in Nunavik, Canada (Boucher et al., 2012). The developing brain during the third trimester of pregnancy is most vulnerable to impacts of methylmercury exposure, in part because it can readily cross the blood-brain barrier and accumulates in fetal umbilical blood (Mahaffey et al., 2011). Recent research provides new evidence for impacts of methylmercury on cardiovascular health of adults (reviewed by Karagas et al., 2012). For example, Roman et al. (2011) synthesized the epidemiological literature and noted that there was sufficient information to use this outcome in regulatory assessments. New information is also emerging about potential impacts of methylmercury on immune health and as an endocrine disruptor (Tan et al., 2009).

Managing and reducing methylmercury exposures in Inuit populations to avoid adverse health effects is extremely complex. Country foods provide essential nutrition (protein and micronutrients) that are not generally replaced when individuals switch away from their traditional diet. Country foods are also important to Inuit for social, cultural, psychological, and spiritual reasons (Donaldson et al., 2010). For these reasons, the benefits of country foods are difficult to replace and must therefore be protected as a nutritional source.

Methylmercury is formed from inorganic mercury naturally present in ecosystems. Levels of inorganic mercury in the global environment, including the Arctic, have been substantially enriched by human activities such as coal combustion and mining (Amos et al., 2013; 2014). Methylmercury is formed when bacteria that require very specific geochemical conditions that are typically associated with low oxygen environments, convert inorganic mercury to methylmercury as part of their natural respiration. After entering the base of the food web (plankton), methylmercury bioaccumulates (concentrates in aquatic food webs) and reaches concentrations of a million times or more those present in water.

Flooding associated with the creation of reservoirs for hydroelectric power enhances the activity of microbial communities responsible for methylmercury production by creating suitable geochemical conditions for them to thrive and labile carbon for their metabolism (Hall et al., 2005, 2004; St Louis et al., 2004, 2001). This mechanism has been shown to occur in reservoirs created for hydroelectric power production. Once produced, methylmercury is released into the overlying water and can be transported downstream and accumulate in the food web. The pulse of methylmercury production is thought to mainly originate from flooded soils and the resulting increases in biological concentrations may be sustained over several decades. Removing organic material and vegetation from the flooded region can minimize effects of flooding on methylmercury production.

The Muskrat Falls project will create a reservoir along the lower Churchill River. The Churchill River supplies over 60% of freshwater inputs and similar proportions of sediment and organic matter (see Chapter 5) to the downstream environment of Lake Melville. Inuit in surrounding communities rely on Lake Melville for their traditional hunting and fishing activities (Figure 6.1).

Inuit communities are exposed to more methylmercury than average Canadians and Americans due to high consumption of fish and marine mammals. Average exposures for Nunatsiavut individuals (3.2 μg/L blood, 0.8 μg/g in hair) participating in the Inuit Health Survey (Chan, 2011a) were higher than the average Canadian (0.7 μg/L blood, 0.18 μg/g in hair). However, no data on individuals from Happy Valley-Goose Bay, North West River or Mud Lake were available prior to this study.

Anticipating the impacts of the Muskrat Falls project on the downstream environment requires an understanding of the major sources and losses of methylmercury and factors affecting uptake into fish and marine mammals in Lake Melville. Here we report the first mercury and methylmercury concentrations measured in the tributaries, water and sediment of Lake Melville. Brouard et al. (1994) found levels in downstream fish were 2.5 times higher compared to upstream, which they attributed to differences in food web structure. Kasper et al. (2012, 2014) showed downstream effects of flooded reservoirs depend on both natural sources and sinks for methylmercury within an ecosystem and its food web structure.

The primary goal of this study was to understand the major sources of methylmercury in Lake Melville biota consumed by Inuit and ecosystem properties that affect accumulation in the food web. To do this, we established baseline concentrations of different mercury species in water, sediment, fish, seal and Inuit individuals. We use the understanding gained from field measurements to develop a model for the potential impacts of flooding on the ecosystem.

Our research addresses the following questions:

- What are the current levels of inorganic mercury and methylmercury in Lake Melville?
- What are the sources of methylmercury to Lake Melville?
- What are the magnitudes and sources of present methylmercury exposure for Inuit in the Lake Melville region?
- How do magnitudes and sources of present methylmercury exposure for Inuit vary by season, demographic group, and community?
- How is the Muskrat Falls reservoir likely to affect Inuit exposures in the Lake Melville region?

6.2. Methods and approach

Ecosystem measurements in Lake Melville

We measured different mercury forms in water and sediment from the Lake Melville region (Figure 6.1) collected in August to September 2012 and June 2013, and ongoing community sampling (initiated in 2014). We collected water samples one metre below the water surface and one metre above the sediment at 27 stations in 2012 and 18 stations in 2013. We collected at least one additional mid-depth sample for stations with depths greater than 50 m. We used this information to develop a budget for the major sources and losses of mercury in Lake Melville, which helps us to understand how changes in mercury inputs from the Churchill River will affect biological concentrations.

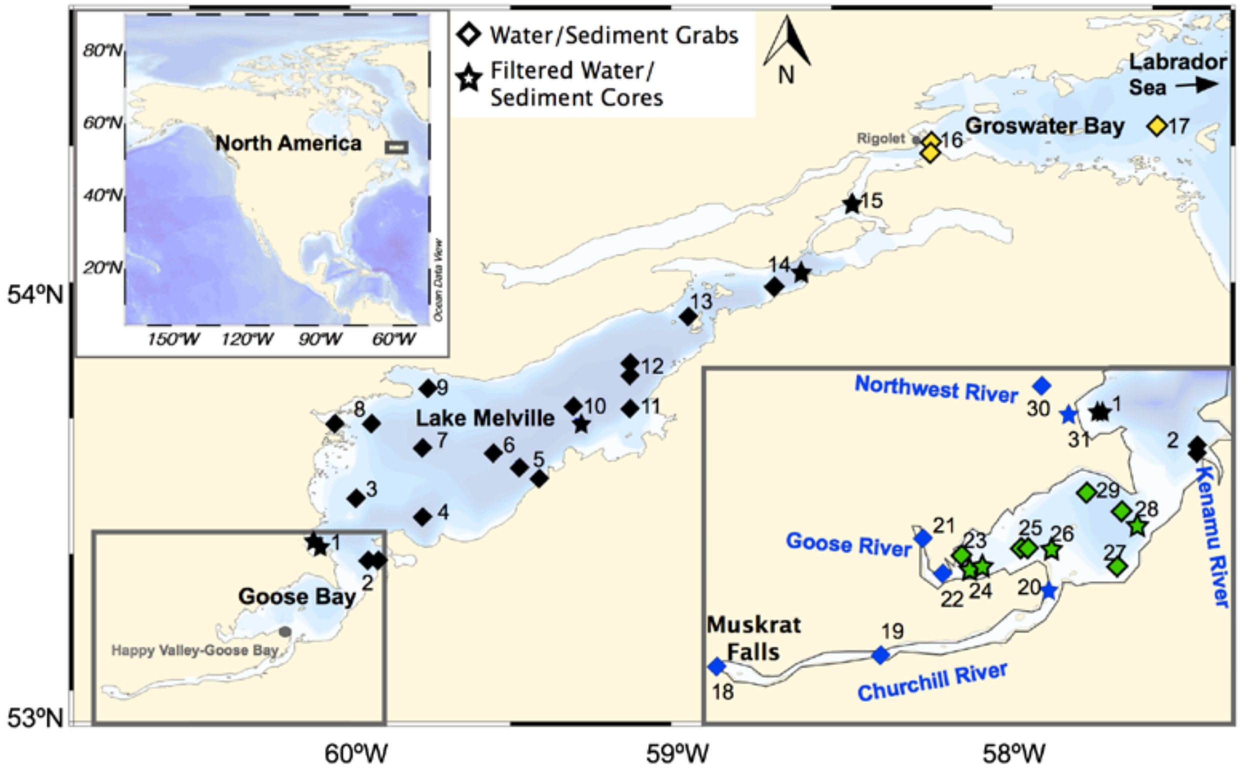


Figure 6.1. Map of Lake Melville and sampling stations. Source: Schartup et al. (2015).

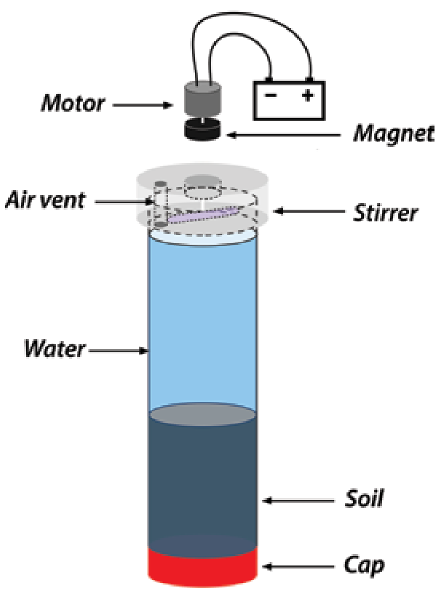


Figure 6.2: Experimental set up used to simulate soil flooding.
Source: Schartup et al. (2015).

We also measured concentrations at the bottom of the Lake Melville food web (phytoplankton) and the small organisms (zooplankton) that consume them from eight stations using a trace metal clean net and cod end. The zooplankton were divided into size fractions as a proxy for their position in the food web.

Two experiments were performed on site. The goal of the first experiment was to determine the rate of methylmercury production in the water and sediment of Lake Melville. The second experiment was designed to simulate flooding in soils that are part of the Churchill River watershed.

To assess the potential impact of the Muskrat Falls reservoir on methylmercury levels in reservoir water, we collected six soil cores from two locations within the planned flooding region of the reservoir (Muskrat Falls, Figure 6.1). Three cores were obtained from a wooded region and three cores next to the Churchill River, where periodic flooding occurs. The litter layer and surface vegetation were removed from all cores. Each core was submerged in water from the Lower Churchill River in benthic flux chambers (Figure 6.2). We monitored the change in methylmercury and nutrients in the overlying water over a period of five days. We measured mercury and methylmercury concentrations in the Churchill River water used for the incubations. We assessed the response of the soils following the flooding by experimentally saturating soils from the region and measuring increases in methylmercury concentrations in overlying river water for five days.

Biological measurements in Lake Melville

We collected fish from a variety of habitats in the Lake Melville ecosystem and analyzed them for total and methylmercury concentrations. We also analyzed the amounts of carbon, nitrogen and mercury isotopes in their tissues that can be used as an indicator of their trophic positions, food webs, terrestrial vs. marine habitat and the environmental sources of methylmercury that are accumulated in the fish. Environment Canada provided us with concentrations of mercury in birds and eggs commonly harvested in the Lake Melville region. A variety of seals were also harvested and analyzed for mercury and various isotopes in collaboration with Environment Canada. These data were used to estimate biomagnification factors between water and fish/seal, baseline exposures of Inuit, and how much time each organism consumed by Inuit spent in the Churchill River, Lake Melville estuary and the open ocean regions. The time spent in each environment was used to link the impacts of Muskrat Falls flooding to changes in biological concentrations.

Dietary survey and biomarker analysis

We assessed current methylmercury exposures for Inuit in the communities of Rigolet, Happy Valley-Goose Bay, and North West River by collecting dietary recall data on country food consumption and measuring concentrations of mercury in hair. Hair mercury levels are a good indicator of methylmercury exposure. Prior to our study, there were only a few measurements of mercury concentrations in Inuit hair from the Lake Melville region. In addition, data on the types and amounts of food consumed were limited.

We designed a food frequency questionnaire, which is a commonly used method for assessing the diet composition of different individuals, to characterize the amounts of aquatic foods consumed by Inuit in the Lake Melville region. After training, research assistants distributed the survey in the communities of Happy-Valley Goose Bay (including the community of Mud Lake), North West River and Rigolet in March, June and September 2014 (see Section 10.3 in the Appendix for additional survey methods). Our goal was to collect information from approximately 10% of the total Inuit population in March and June and as many Inuit community members as possible in September. Total participation in our survey was 231 in March, 294 in June and 1,057 in September. Of these participants, 157 in June and 499 in September provided hair samples from the occipital region of the scalp (back of the head) in sufficient quantity for mercury exposures to be directly measured. The survey collected information on consumption of 65 local foods and 24 store-bought seafood items. Participants were asked to recall their consumption (meals per day) over the previous 24 hours, one-month and three months. They were also asked to identify their typical meal sizes by choosing among clay serving models for each reported food.

We measured total mercury in the two-centimetre proximal end of all hair samples (hair close to the root). Total mercury concentrations were quantified by thermal decomposition, amalgamation, and atomic absorption spectrophotometry [EPA method 7473 (U.S. EPA, 2007)] using a Nippon Direct Mercury Analyzer. The instrument was calibrated with a liquid inorganic mercury standard, with daily verification across a range of mercury masses using two certified reference materials (MESS-4 and TORT-3, National Research Council Canada). Precision, estimated by replicate analysis of the reference materials and duplicate hair samples, was better than 4% and 9% (RSD), respectively.

Methylmercury exposures can be assessed indirectly by multiplying the concentration in different foods by the amounts consumed or directly by the measured levels of mercury in hair. We used both approaches in our study. Methylmercury concentrations in different food items were obtained from direct measurements of mercury content for some local foods and an extensive literature review for others.

The research design prioritized local involvement and capacity building. Survey and hair sampling work was carried out by a total of 28 local (26 Inuit) Research Assistants, who completed two days of training, and worked an approximate total of 1,566 person-hours. Project communications included community information sessions, pamphlets, direct mail-outs to participants, posters and social media updates. Focus group sessions were conducted with Community Research Advisory Committees in all Upper Lake Melville communities and Rigolet, to improve the food frequency survey during its development. Changes to survey and hair sampling dates and sample sizes were made based on knowledge and advice provided. Likewise, the addition of local terms to the initial survey, and the assistance that the Community Research Advisors provided the study team in understanding local nuances related to country foods, how they are eaten and where they are obtained, aided with interpretation of results. Informal contact with Community Research Advisors also assisted with participant recruitment, local transportation and project promotion.

This work builds on research done by the Inuit Health Survey by documenting dietary information for Inuit living in Upper Lake Melville communities (North West River, Happy Valley-Goose Bay and Mud Lake, home to over 2,300 Inuit) who were not included in the Inuit Health Survey. We capture dietary changes resulting from the ban placed on the George River caribou hunt in 2013, and are able to distinguish community-level consumption patterns, as local knowledge suggested substantial differences.

6.3. Methylmercury production and biological uptake in the ecosystem

Rivers are major sources of mercury to Lake Melville

The surface of Lake Melville (upper 50 m) is strongly stratified (Figure 2.2), thus mercury inputs from rivers are visible in the low salinity surface waters and travel far downstream toward the outer Labrador Sea (Figure 6.3). Rivers supply the nutrients and terrestrial organic carbon (see Chapter 5 and Figure 6.3) that drive algal production (primary production) in Lake Melville. These inputs are also confined to the surface layer because of the density gradient in Lake Melville that remains intact throughout the year but breaks down in Groswater Bay.

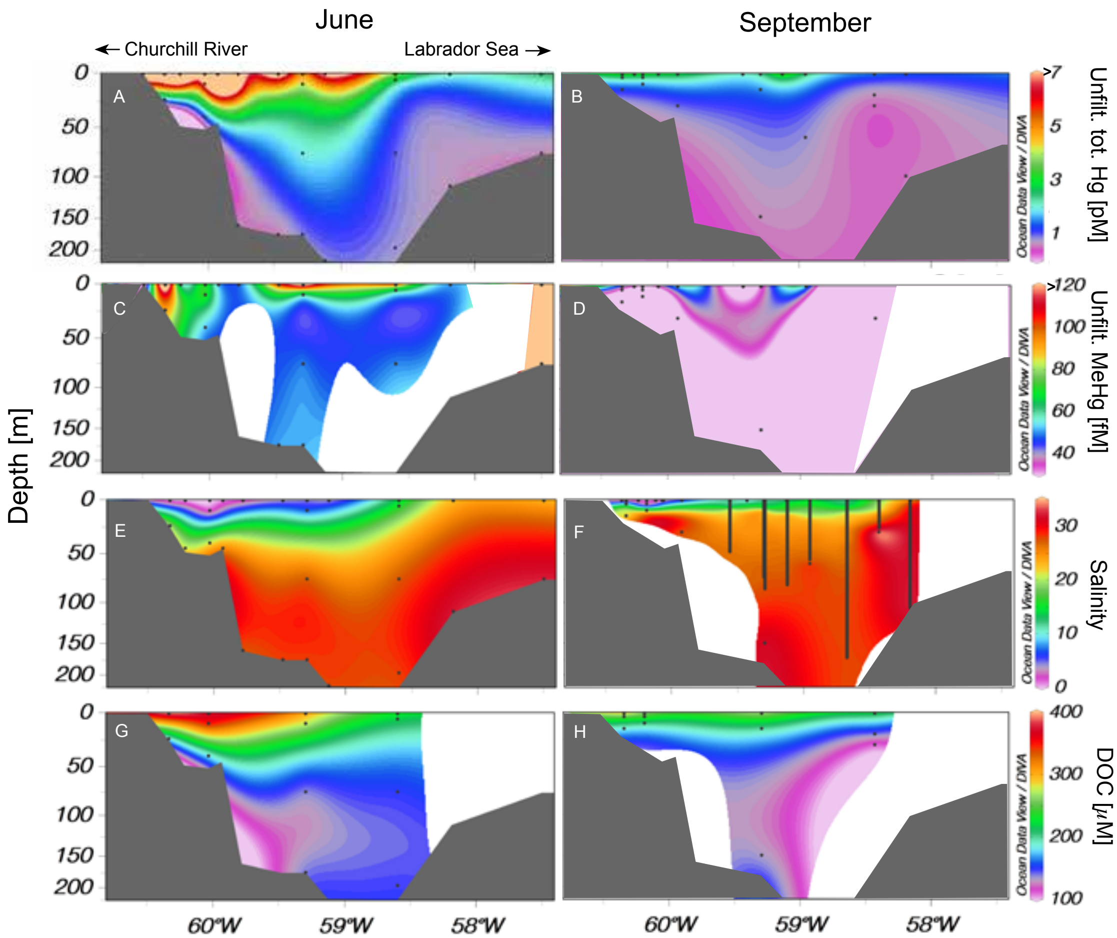


Figure 6.3. Cross-sectional view of total Hg and MeHg concentrations in unfiltered seawater in Lake Melville extending from the freshwater inputs on the left (Churchill River) to outer marine regions (Groswater Bay) on the right that extend into the Labrador Sea. (A and B) Unfiltered total Hg. (C and D) Unfiltered total MeHg. (E and F) Salinity. (G and H) Dissolved organic carbon. Samples were collected between August 31 and September 8, 2012 and June 11–19, 2013. Black symbols represent sampling points. Bars in F represent a measurement frequency of 0.1–0.5 m. *Source: Schartup et al. (2015).*

Figure 6.4 shows that rivers are the major source of mercury to Lake Melville and make up more than 85% of total inputs. Most of the methylmercury presently found in Lake Melville is produced *in situ* in the water column. This is a major finding, because in most estuarine systems methylmercury is thought to be primarily produced in the sediment and diffuse into the water column. Water column based production may lead to faster response of the system to changes upstream (e.g. change in terrestrial organic carbon inputs).

Rivers are the second largest source of methylmercury to Lake Melville (Figure 6.4). Methylmercury produced in terrestrial ecosystems is bound to terrestrial dissolved organic carbon in rivers (Jonsson et al., 2014). Terrestrial dissolved organic carbon stabilizes the methylmercury and allows it to be transported downstream. Methylmercury bound to terrestrial dissolved organic carbon is readily taken up at the base of the food web where it accumulates in marine food webs (Figure 6.5). This means that enhancements in methylmercury produced from flooding of the region upstream of the Muskrat Falls dam are likely to be transported downstream and enter Lake Melville food webs.

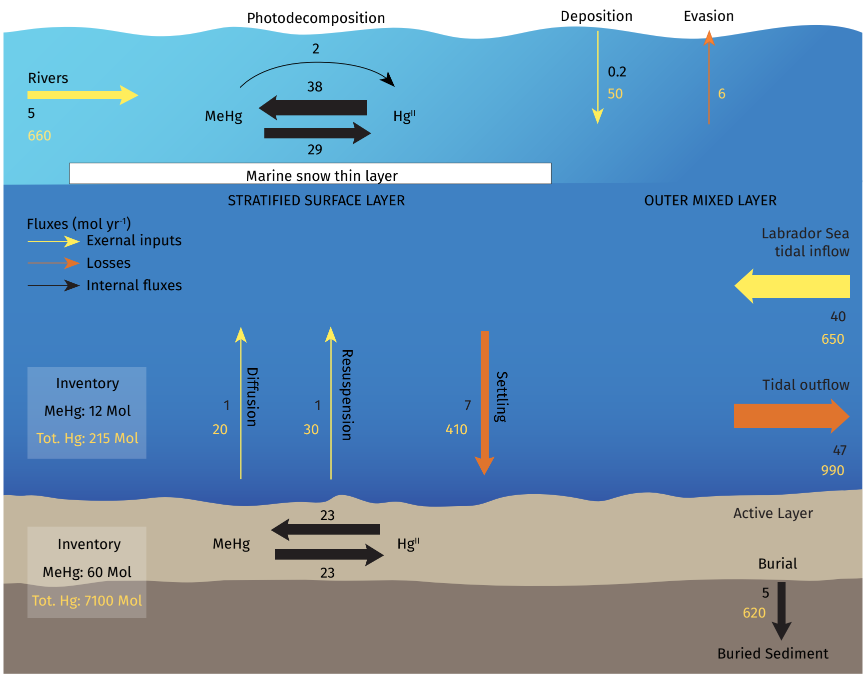


Figure 6.4. Annual mass budget for methylmercury (MeHg, indicated in black) and total mercury (Hg, indicated in light orange) in Lake Melville. Mass flow rates are shown as mol Hg yr^{-1} and the total amounts of methylmercury and mercury in the water and sediment of Lake Melville are given in moles. Yellow arrows represent external sources of MeHg and total Hg to the water column, orange arrows represent losses, and black arrows indicate internal fluxes. *Source: adapted from Schartup et al. (2015).*

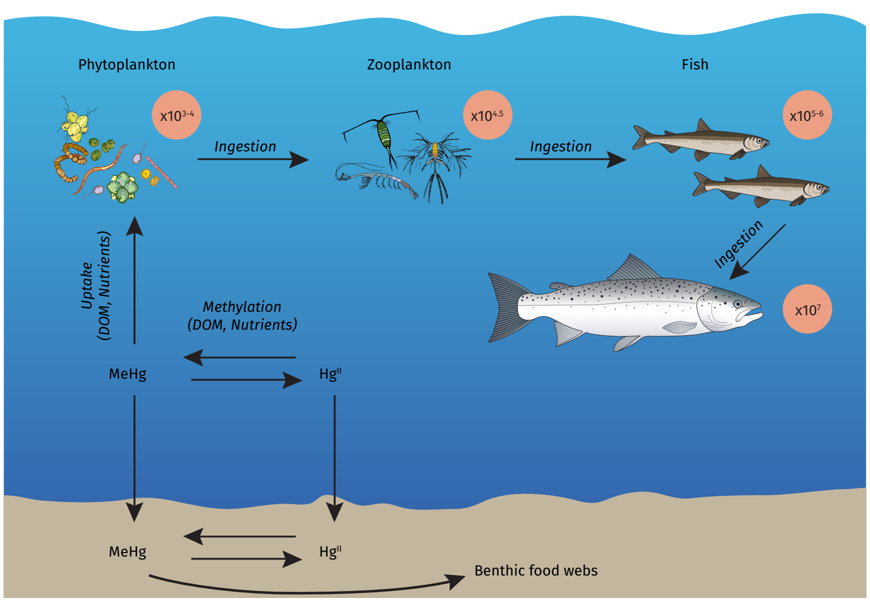


Figure 6.5. Diagram of methylmercury (MeHg) accumulation in food-webs and main parameters affecting the biological uptake, such as methylmerury production (methylation), dissolved organic matter (DOM) and nutrients. Increases in methylmercury concentrations from initial concentrations in water are indicated in orange circles.

Stratification in Lake Melville enhances methylmercury bioaccumulation

In marine systems the majority of methylmercury bioaccumulation (x10^3 to 10^5) occurs between seawater and plankton (Figure 6.5). Figure 6.6 shows methylmercury accumulation in plankton in Lake Melville and shows a sharp increase in methylmercury concentrations between phytoplankton and 200 to 500 µm zooplankton. Highest methylmercury concentrations and bioaccumulation factors (BAF; biological concentrations divided by water column concentration) are observed in the estuarine region with stable year-round stratification near the river mouth (Goose Bay) and the lowest in the more well-mixed outer marine areas (Groswater Bay) (Figure 6.6). In the estuary, the fraction of total mercury as methylmercury (% MeHg) in different size fractions of plankton increases from <10% in the seston (5 to 200 µm) to approximately 80% in the 500 to 1000 µm fractions (Figure 6.6). Similar increases are not observed in Groswater Bay approaching the Labrador Sea.

We postulate that enhanced bioaccumulation in the stratified regions of the estuary compared to the outer water column reflects a vertically concentrated zone of methylation and biological activity (bacterial activity, phytoplankton and grazers). Stratification of the water column facilitates the formation of thin layers of organic material by providing a density surface where settling marine snow reaches neutral buoyancy and can form a mucous rich mat of aggregated phytoplankton during the spring bloom. The thin layer can collect smaller settling detritus and commonly contains the majority of the phytoplankton biomass (50 to 75%) in the water column (Berdalet et al., 2014). In oligotrophic systems where food for grazing zooplankton is limited and a large proportion of the algal biomass is present in thin layers, herbivorous and predatory zooplankton are also concentrated in this layer (Benoit-Bird et al., 2010). Enhanced microbial activity and organic matter degradation in such a thin layer would explain elevated methylmercury production and zooplankton concentrations in the stratified regions of the Lake Melville estuary where BAFs also peak (Figure 6.6).

Our research on methylmercury production and food web uptake shows some unusual characteristics of Lake Melville that make it particularly efficient at magnifying methylmercury in food webs. We found active conversion of inorganic mercury from rivers in the water column of the estuary that is facilitated by the types of organic carbon entering the estuary from

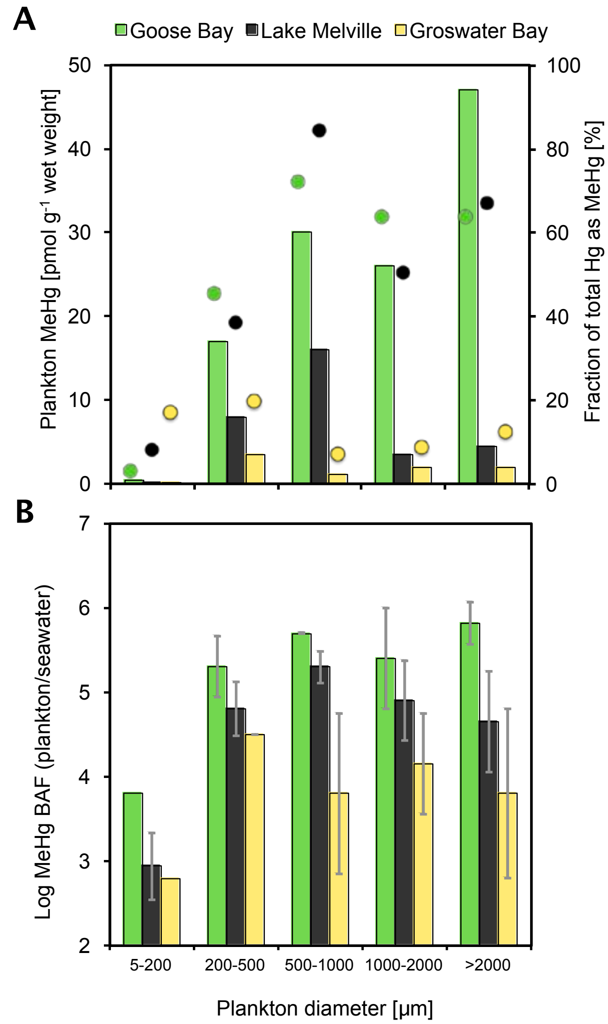


Figure 6.6. Methylmercury in plankton collected in June 2013. Panel A shows methylmercury (MeHg) concentrations (bars) measured in five size classes of plankton across the main sampling regions. Sampling regions are denoted by black (Lake Melville), green (Goose Bay) and yellow (Groswater Bay). Panel B shows methylmercury bioaccumulation factors (BAFs) calculated for each size fraction of plankton across the sampling regions (plankton methylmercury divided by seawater concentrations). Phytoplankton fall within the 5–200 µm size class and zooplankton comprise the larger fractions. *Source: Schartup et al. (2015).*

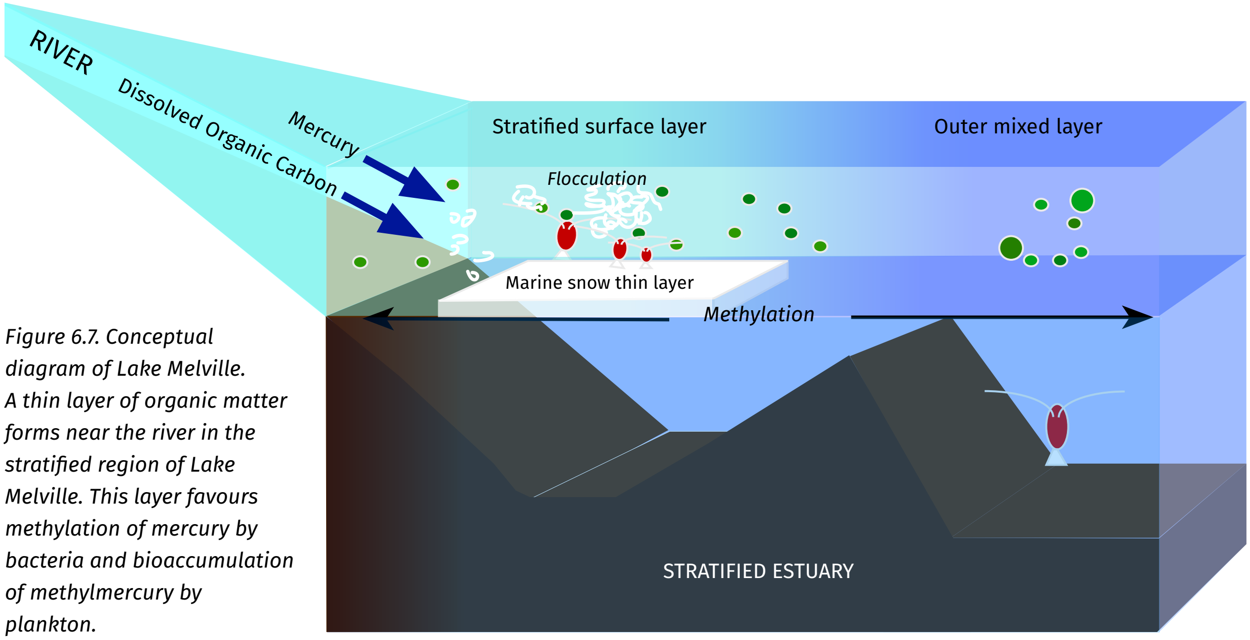


Figure 6.7. Conceptual diagram of Lake Melville. A thin layer of organic matter forms near the river in the stratified region of Lake Melville. This layer favours methylation of mercury by bacteria and bioaccumulation of methylmercury by plankton.

rivers. Methylmercury production in most estuaries at lower latitudes has previously been attributed to bottom sediment, which takes longer to enter the water column and fish.

The division of Lake Melville into a relatively fresh surface layer and a saline bottom layer mainly from the Labrador Sea constrains primary productivity, methylmercury production and several levels of the food web (plankton) in surface waters (Figure 6.7).

Bioaccumulation factors for methylmercury in Lake Melville (concentrations in zooplankton divided by concentrations in seawater) are greater than for mid-latitude ecosystems, suggesting the system is especially vulnerable to increased inputs of both methylmercury and inorganic mercury that may be methylated in the water column.

6.4. Methylmercury concentrations in country foods

Figure 6.8 shows methylmercury concentrations in frequently consumed foods. Locally caught wildlife represents a large fraction of consumed food and about 70% of the total methylmercury exposure. A significant number of the species consumed are from the freshwater or estuarine environment, which means they spent their whole or part of their lives in river or Lake Melville waters. We calculated the fraction of lifespan that different species spent in marine, estuarine and river environments using reported species behavior and their isotopic composition.

6.5. Current methylmercury exposures in the Inuit population

Methylmercury exposures of Inuit in Lake Melville region higher than in Canadian population

Similar to the previous work of the Inuit Health Survey, our results show Inuit in the Lake Melville region have higher methylmercury exposures than those of the general Canadian population. Half of the hair samples from Inuit residing in the Lake Melville region were above 0.38 µg Hg/g in the Spring and 0.51 µg Hg/g in the Fall and the highest five of every 100 samples in September averaged 2.45 µg Hg/g (Figure 6.9). For the general population in Canada, prior work shows half of the samples were above 0.20 µg Hg/g and the top five out of every hundred averaged 1.18 µg Hg/g (Lye et al., 2013). Concentrations of Hg in less than 10% of Inuit hair samples exceeded the level corresponding to Health Canada's reference dose for women of childbearing age and children (approximately 2 µg Hg/g hair). No women of childbearing age (16–49) or children were found to exceed this exposure level.

Methylmercury exposures among Lake Melville Inuit appear to be lower than other Inuit communities. The mean hair mercury levels reported by the Inuit Health Survey were 1.5 µg/g in Nunavut (Chan, 2011b) and 2.6

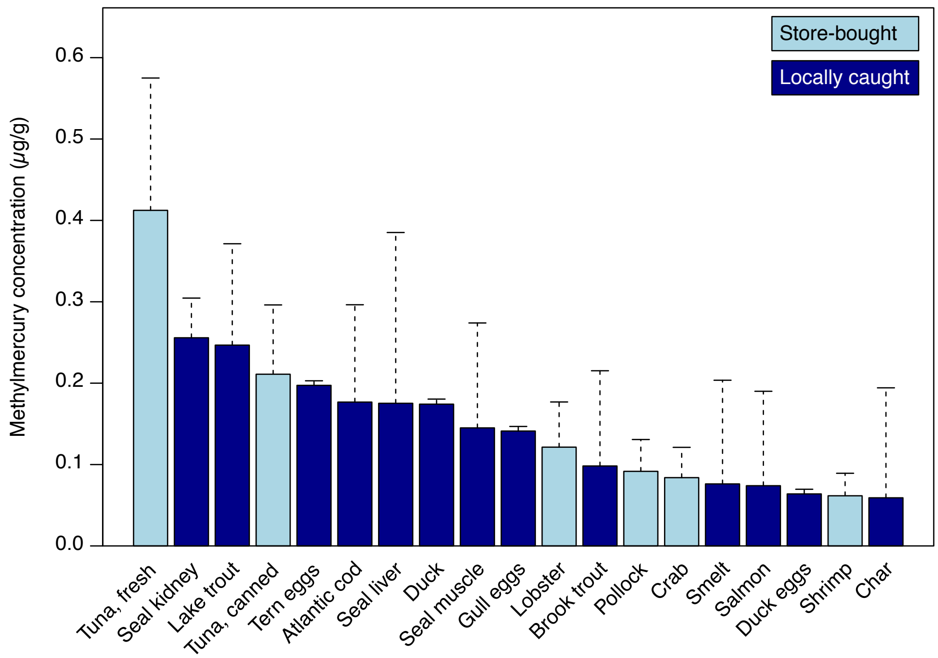


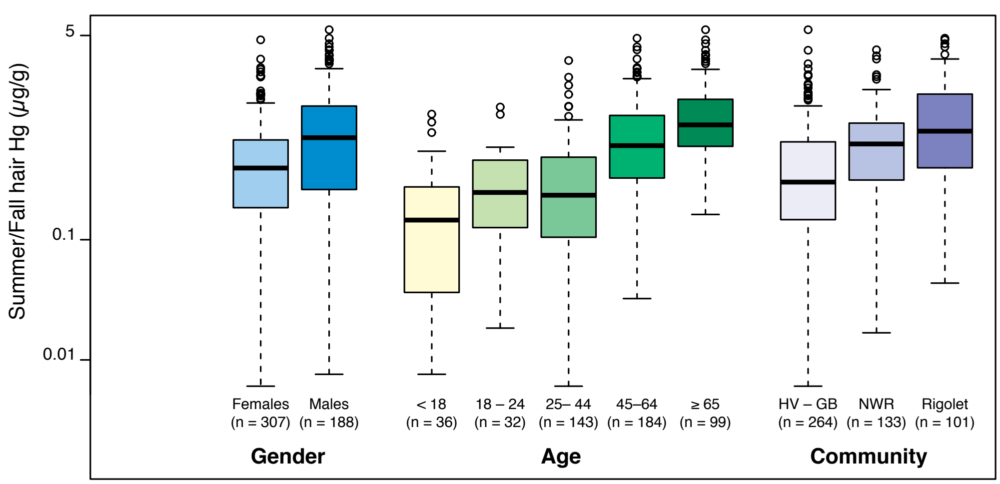
Figure 6.8. Methylmercury concentrations in commonly consumed local and store-bought foods. *Source: Calder et al. (in prep).*

µg/g in Nunavik (Dewailly et al., 2004). The Inuit Health Survey also found lower levels among all Nunatsiavut Inuit (including Rigolet but excluding Happy Valley-Goose Bay, Mud Lake and North West River), with a mean value of 0.8 µg Hg/g (Chan, 2011a). These values are geometric means and converted from the reported blood concentrations (WHO 1990).

Figure 6.9 presents hair mercury distribution by gender, age and community. We find that methylmercury exposures were higher among men than among women and children, which is consistent with men reporting a greater consumption of locally harvested foods than women and children. We find higher exposures in older segments compared with younger segments of the population, also driven by greater consumption of local foods. We measured higher methylmercury exposures in Rigolet and North West River than in Happy Valley-Goose Bay. Survey participants in Rigolet reported consuming more seal liver and seal meat compared to those in Happy Valley-Goose Bay.

Figure 6.10 shows the relative contribution of different food sources consumed by Inuit (n=1057) in 2014 to total methylmercury exposures. Locally harvested salmon, cod and trout account for the largest fractions of Lake Melville Inuit methylmercury exposures. Cumulatively, locally harvested foods account for 67% of total methylmercury exposures across seasons, with the remaining fraction from store-bought fish and shellfish.

Figure 6.9. Measured hair mercury concentrations stratified by gender/ age and community. HV-GB=Happy Valley-Goose Bay, NWR= North West River. Happy Valley-Goose Bay includes the nearby community of Mud Lake. *Source: Calder et al. (in prep).*



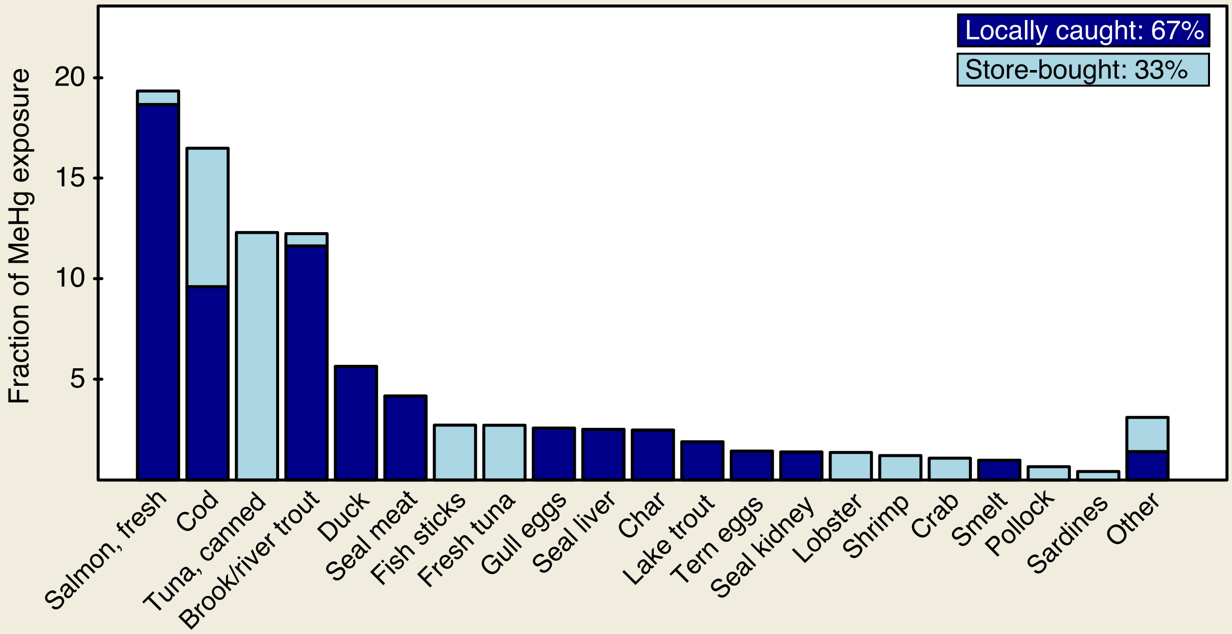


Figure 6.10. Methylmercury exposure sources for the Inuit communities in Happy Valley-Goose Bay, North West River and Rigolet in Fall 2014. Top food sources are shown, and the category "other" includes 36 local and store-bought foods. Locally harvested indicates foods from the Lake Melville environment. "Salmon, fresh" excludes landlocked salmon (ouananiche). Source: Calder et al. (in prep).

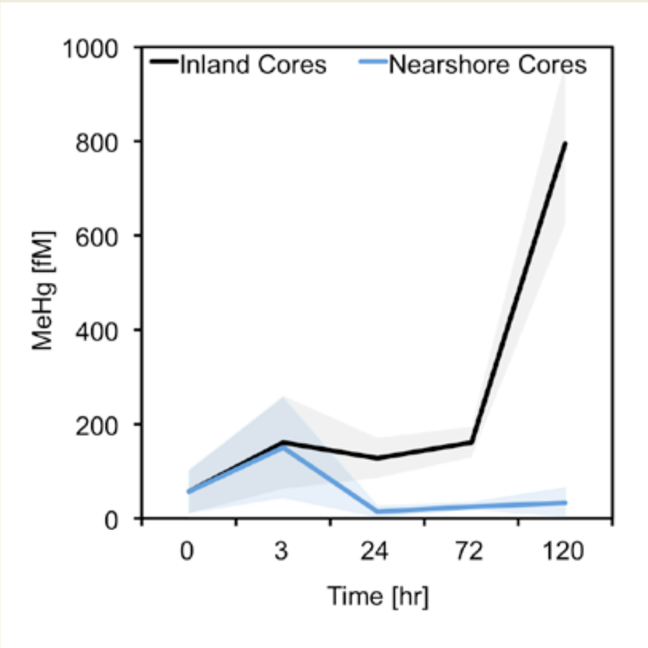


Figure 6.11. Changes in methylmercury (MeHg) concentrations over time in overlying water of experimentally flooded soils from the Lake Melville watershed. Results are from six cores from the planned reservoir area. Three were collected near the Churchill River and three from the dry inland regions that will be flooded. Source: Schartup et al. (2015).

6.6. **Potential impacts of Muskrat Falls flooding on methylmercury in Lake Melville**

Flooding experiments indicate pulse in methylmercury production occurs within 72 hours

Figure 6.11 shows a pulse in methylmercury production within 72 hours of flooding inland soil cores from the future Muskrat Falls reservoir area. There is a 14-fold increase in methylmercury concentrations within 120 hours from inland soil cores and no change in the nearshore soil methylmercury concentrations in this period. The nearshore soil cores already experience occasional flooding.

Organic material stimulates the activity of bacteria responsible for converting mercury present in the soil to methylmercury. Current plans for preparation of the reservoir area involve partial clearing of trees and no clearing of litter or other vegetation. As such, we can expect that the actual pulse of methylmercury to the Lake Melville ecosystem will be much greater.

We constructed three scenarios to bound the potential magnitude of changes in methylmercury concentrations in the Churchill River and Lake Melville following flooding. Variables considered included: 1) the carbon content of the watershed; 2) degradation of methylmercury as it travels from the reservoir into Lake Melville; 3) amount of time organisms consumed by Inuit spent in the river, Lake Melville or outer marine region; and 4) amounts and types of country foods consumed by Inuit in the communities of Happy Valley-Goose Bay (including Mud Lake), North West River and Rigolet.

To construct scenarios for the potential pulse in methylmercury production in the flooded reservoir, we reviewed the experimental literature on the relationship between methylmercury production and carbon content of the watershed. These data were used to develop an empirical relationship between reservoir methylmercury peak production and organic carbon content (Louis et al., 2004; Hall et al., 2005). We used GIS data on land cover and type in the proposed area to be flooded to derive estimates of the organic carbon content.

Methylmercury produced in the impoundment can potentially be demethylated by bacteria or photodegraded as it travels to Lake Melville. We note that recent research suggests binding to terrestrial dissolved organic carbon from the watershed can make methylmercury very resistant to degradation (Jonsson et al., 2014). We assume degradation of up to 70% of the total methylmercury produced in the flooded reservoir (Schartup et al. 2015; Calder et al., in prep). This is a conservative approach (high estimate of degradation) because we neglect water-column production of methylmercury facilitated by eroded soils (St. Louis et al. 2003, 2004) and do not account for the export of predominantly methylmercury-rich bottom waters from impoundments (Kasper et al., 2014).

Because Lake Melville is stratified, freshwater entering the system does not mix with the entire water column but remains at the surface. We adapt the Lake Melville mercury model (Figure 6.4) published by Schartup et al. (2015) to isolate the low-salinity upper 10 m of the water column that is most relevant for the estuarine food web. We use this model to calculate changes in methylmercury levels in the upper layer for different methylmercury input scenarios from the Churchill River and calculate corresponding changes in fish and human exposures.

In summary, we defined three methylmercury levels reflecting a range of flooding scenarios as follows:

- *Low methylmercury levels*: Assumes removal of **topsoil**, vegetation & trees; rapid decomposition of methylmercury in the river.
- *Moderate methylmercury levels*: Assumes **partial clearance** of trees & brush, moderate decomposition of methylmercury in the river.
- *High methylmercury levels*: Assumes **partial clearance** of trees & brush; little decomposition of methylmercury in the river.

6.7. Potential changes in methylmercury exposures of Inuit resulting from Muskrat Falls flooding

Hundreds of Inuit pushed above regulatory guidelines for exposure without full clearing of the reservoir

Figure 6.12 shows the changes in methylmercury exposures resulting from the three scenarios. Even under the low scenario, which requires complete removal of topsoil, vegetation and trees, and rapid decomposition of methylmercury in the downstream environment, there will be an overall increase in methylmercury exposures.

Under the scenario where carbon-rich surface soil is not removed before flooding, median exposures may increase by nearly 50% to greater than 100%. Roughly 10 to 20% of Inuit living around Lake Melville are expected to exceed Health Canada's provisional tolerable daily intake (pTDI) of 0.2 µg/kg body weight/day after flooding compared to 4% at baseline. The 95th percentile (roughly 150 Inuit in the Lake Melville region) may increase from roughly the pTDI at baseline by roughly 350%.

Removal of surface soil and litter is likely to substantially reduce the magnitude of methylmercury production. It may reduce by roughly two thirds the number of Inuit expected to exceed the Health Canada pTDI.

Our analysis suggests the number of Inuit potentially pushed above the Health Canada guideline for exposure (0.2 µg/kg body weight/day) ranges from 32 individuals under the low scenario (if the reservoir is completely cleared, including topsoil) to >200 individuals under the high scenario. This number increases to >50 under the low scenario and >400 under the high scenario if the U.S. EPA reference dose (0.1 µg/kg body weight/day) is used instead of the Health Canada guideline.

Rigolet residents are at higher risk of increased mercury exposures due to flooding because of their greater reliance on locally caught food. Under the high scenario, up to 46% of residents exceed the Health Canada guideline for adults and 66% of residents are above the U.S. EPA reference dose.

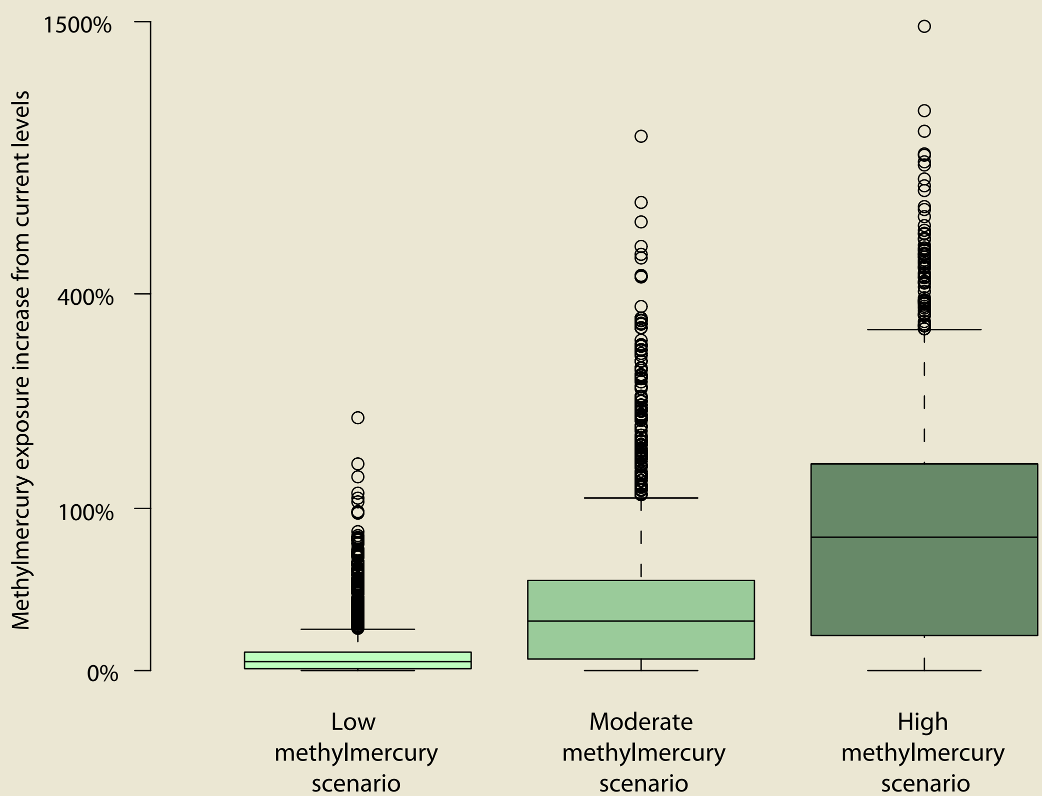


Figure 6.12. Modelled changes in methylmercury exposure under the three scenarios. Middle line in box indicates median (50% above this value); top of box indicates 75th percentile (25% above this value). Approximately 10% of values are above the top whisker (uppermost horizontal line). Source: Calder et al. (in prep).

*Figure 6.13. **Projected percentage of the population exposed to methylmercury levels above the Health Canada guideline under three flooding scenarios.** Source: Calder et al. (in prep).*

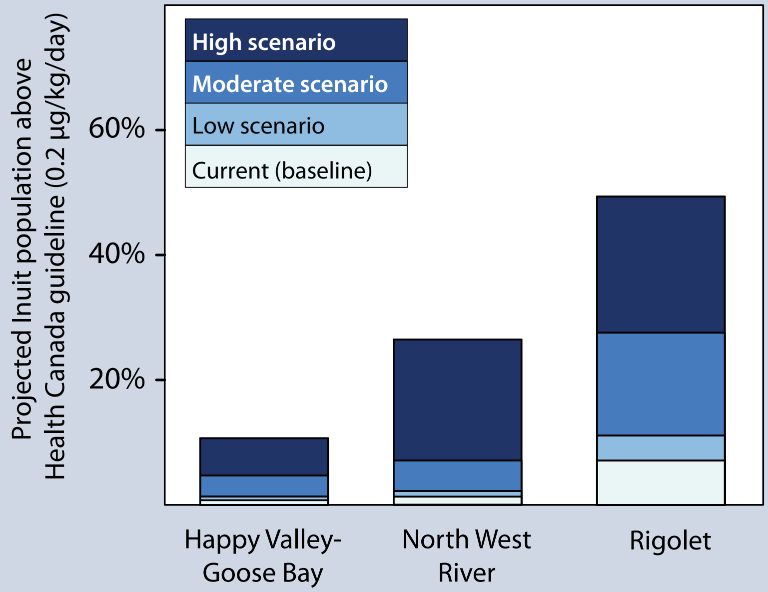
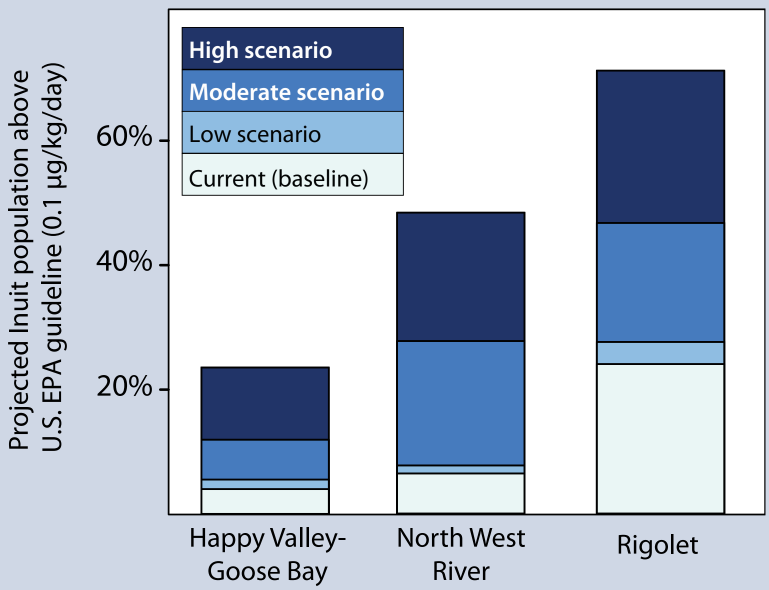


*Figure 6.14. **Projected percentage of the population exposed to methylmercury levels above the U.S. EPA reference dose under three flooding scenarios.** Source: Calder et al. (in prep).*



Churchill River.

Credit: *Build Films*

7. CONCLUDING COMMENTS

Lake Melville is a unique subarctic estuary that supports high species diversity and productivity, but it is also more: it is a 'grocery store' for thousands of Inuit and non-Inuit residents that live on its shores and regularly harvest country food such as fish, marine mammals, and waterfowl from its waters; a critical component of travel infrastructure in a remote region where residents depend on ice to move across the landscape for much of the year; and a place with rich historical and culture meaning for Inuit rooted in a relationship that spans many generations. In this report, we have presented findings regarding physical, chemical, and biological processes and dynamics that are part of and shape Lake Melville, including past influences of hydroelectric development and climate change, to improve our understanding of this valued and complex ecosystem.

A major emergent theme in this report is the enormous influence of the Churchill River on Lake Melville. The Churchill River is Lake Melville's largest freshwater source, supplying over 60% of the freshwater that enters the estuary. Evidence in this report demonstrates that the Churchill River has a significant effect on numerous processes in Lake Melville: physical lake dynamics; ice formation and transport; sediment and organic carbon cycling, which supports the base of the food web; and the production and bioaccumulation of methylmercury in the food web. Developing a robust understanding of the influence of the Churchill River on Lake Melville is critically important, as changes to the river are expected due to the development of Muskrat Falls. The findings documented in this report provide an updated and authoritative understanding of key aspects of the Lake Melville ecosystem. They also present projections of future changes related to Muskrat Falls and the compounding effects of climate change. This new knowledge is made available to support science-based management and monitoring of the Muskrat Falls project and its projected downstream impacts on the Lake Melville ecosystem and the health of Inuit who depend on it.

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$\delta^{13}C$	Stable carbon isotope
ADCP	Acoustic Doppler Current Profilers
AMO	Atlantic Multidecadal Oscillation
BAF	Bioaccumulation factors
CIS	Canadian Ice Service
Cs	Cesium
CTD	conductivity-temperature-depth
DOM	Dissolved organic matter
EA	Environmental Assessment
EIS	Environmental Impact Statement
GPS	Global Positioning System
Hg	Mercury
LIL	Labrador Inuit Lands
LILCA	Labrador Inuit Land Claims Agreement
LISA	Labrador Inuit Settlement Area
MeHg	Methylmercury
MW	Megawatt
NAO	North Atlantic Oscillation
NHANES	National Health and Nutrition Examination Survey
OC	Organic carbon
Pb	Lead
POC	Particulate organic carbon
psu	Practical Salinity Unit
pTDI	Provisional tolerable daily intake
Ra	Radium
RSD	Relative standard deviation
SAR	Synthetic Aperture Radar
SLP	Sea level pressure
TOC	Total organic carbon
SmartICE	Sea-ice Monitoring And Real-Time Information for Coastal Environments
TSS	Total suspended solids

10.1. **Climate**

Table 10.1. Mean dates of freeze-up and break-up at analysed Lake Melville locations, along with standard deviations. All are given in Julian Day; for freeze-up, dates larger than 365 indicate freeze-up occurs in January (e.g. 367 implies Jan. 2nd; 370 implies Jan. 5th).

Grid Points	*Mean Date of Freeze-up*	*Standard Deviation of Freeze-up Date*	*Mean Date of Break-up*	*Standard Deviation of Break-up Date*	*Mean Ice Season Length (Days)*	*Standard Deviation of Ice Season Length*
X1	354	12	148	10	157	16
X2	367	16	146	14	141	22
X3	359	13	150	10	155	15
X4	369	17	152	10	147	22
X5	368	15	152	11	148	20
X6	368	16	152	12	148	22
X7	366	17	152	11	150	21
X8	367	16	151	12	150	22
X9	364	16	149	13	149	23
X10	359	12	136	17	140	24
X11	356	13	155	11	161	16
X12	364	16	148	13	148	25
X13[1]	429	51	43	47	-30	78
X14[1]	430	46	78	47	10	76

Note: [1]Locations X13 and X14 give unusual results because they are close to the Rigolet Narrows and remain ice-free through much of the winter

10.2. **Sediments and organic carbon**

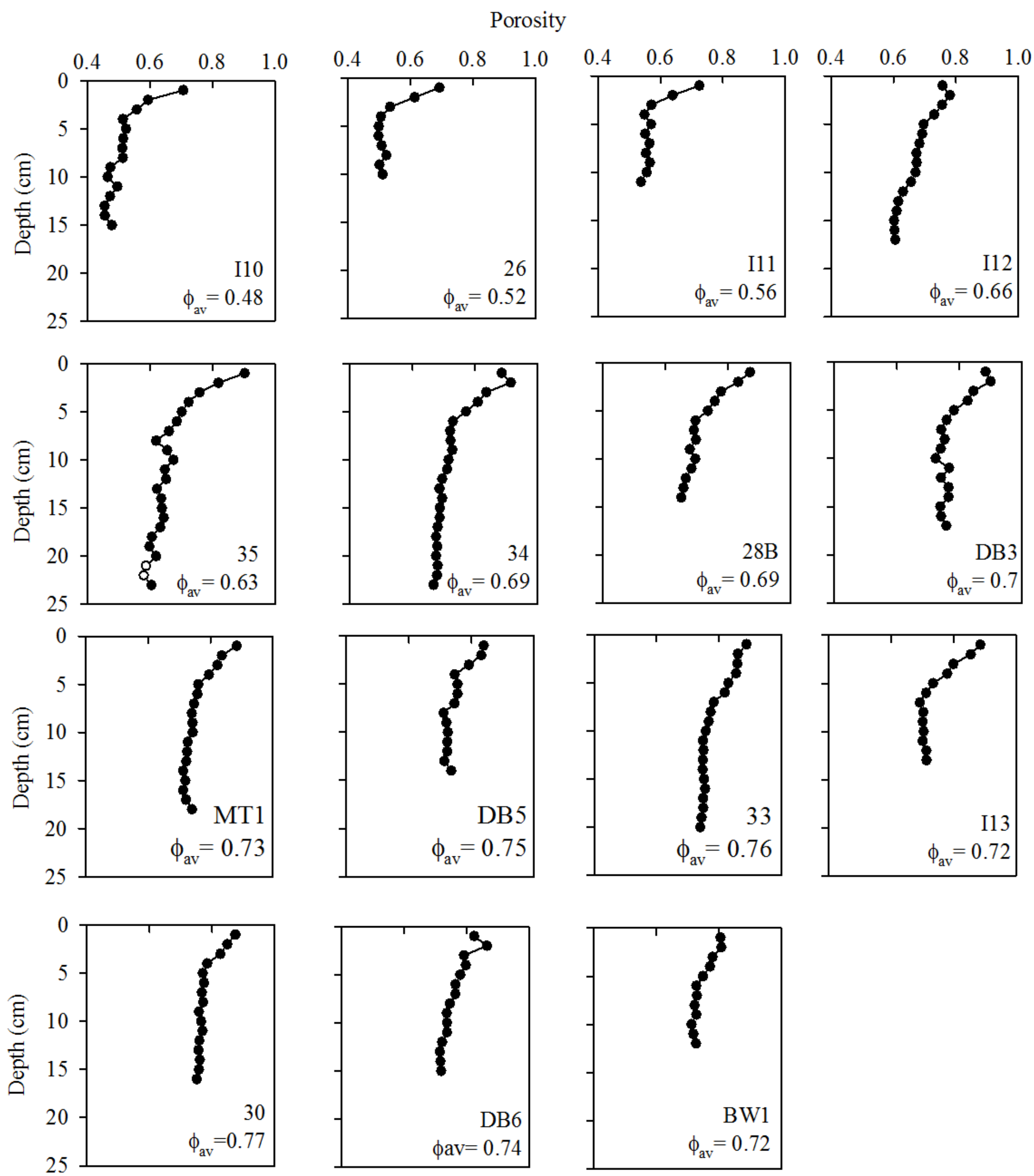

Figure 10.1. Porosity profiles of sediment cores. Values for average porosity (ϕ^{av}) are provided for each core. Core name is shown in the bottom right corner of each plot.

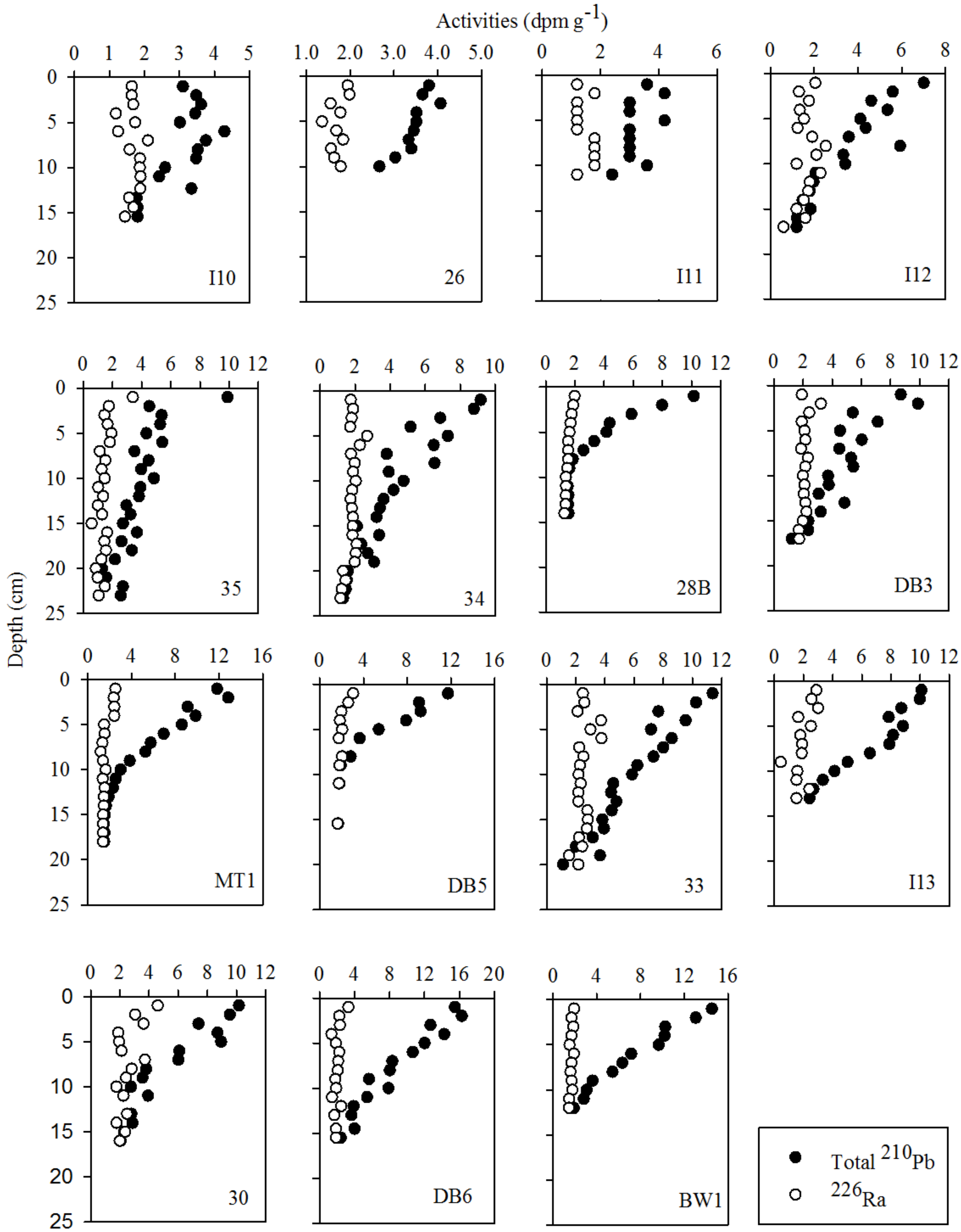

Figure 10.2. Profiles of total ^{210}Pb (black dot) and ^{226}Ra (white dot) activities in the cores. Core name is shown in the bottom right corner of each plot.

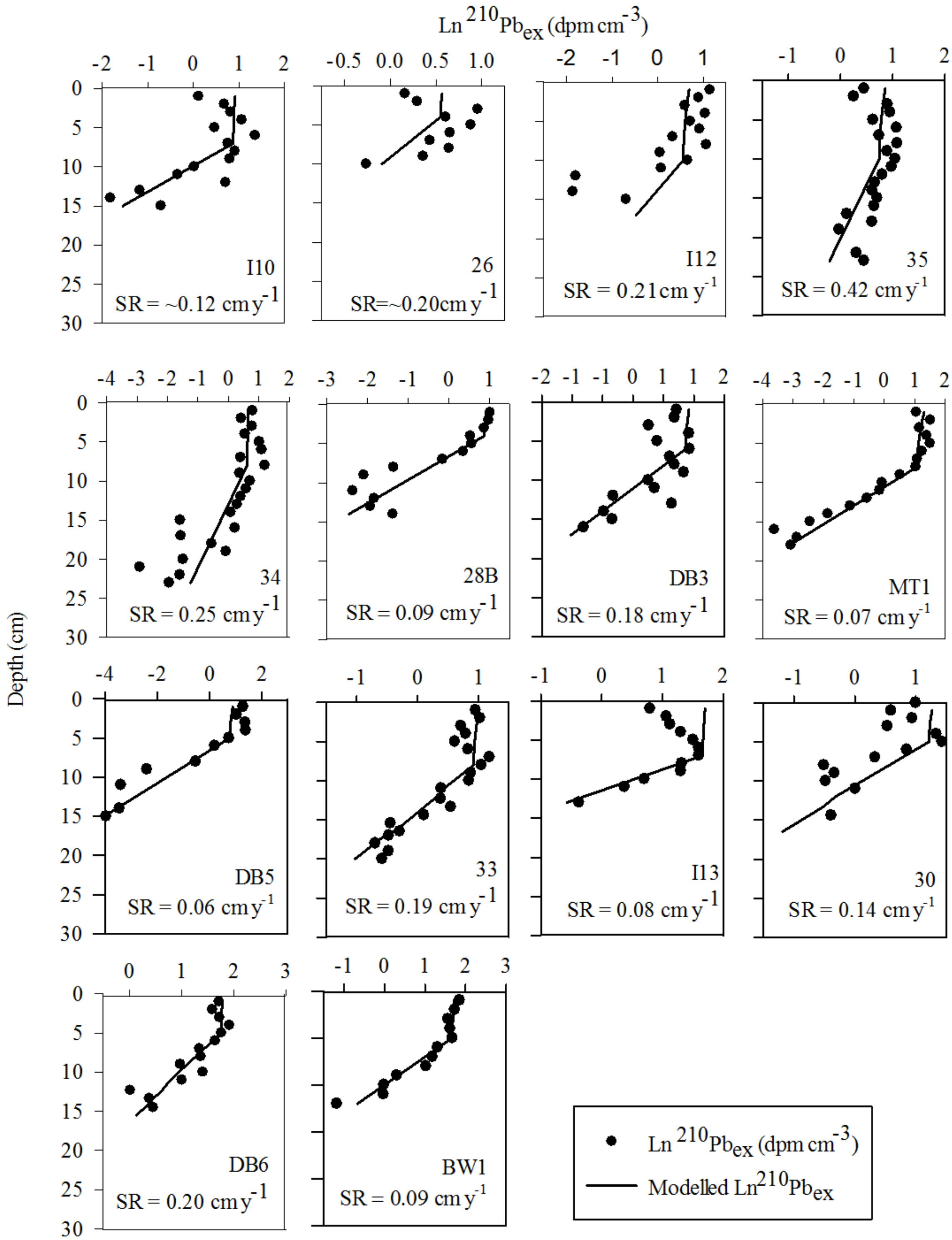

Figure 10.3. Profiles of measured (black point) and modelled (line) natural log excess ^{210}Pb (Ln $^{210}Pb_{ex}$) and ^{137}Cs activity. Core name and sedimentation rates are shown in the bottom right corner of each plot. Sedimentation rates beginning with "~"could not be validated because of incomplete or uniform ^{137}Cs profiles. Observed coarser material at 20 and 21 cm in core 35 resulted in abnormally low activities and were excluded from modelling.

Table 10.2. Summary of $^{210}Pb_{ex}$ and ^{137}Cs inventories (± 1σ) (Eq.4), $^{210}Pb_{ex}$ flux at the sediment water interface (determined by multiplying the inventory by the ^{210}Pb decay constant of 0.03114 y^{-1}) and the ratio (R) of $^{210}Pb_{ex}$ flux to the expected, steady-state vertical atmospheric deposition of ^{210}Pb to Lake Melville region (~0.734 dpm cm^{-2} y^{-1})

Core	Core Length (cm)	Water Depth (m)	Φ_{av}	SML (cm)	C_0 (dpm cm^{-3})	K_{b1} (cm^2 y^{-1})	SR (cm y^{-1})	MAR (g cm^{-2} y^{-1})
I10[2]	15	25.5	0.48	6	7	15	~0.12	~0.16
26[1,2,3]	10	49	0.52	7	5	8	~0.2	~0.27
I12	17	48	0.66	9	10	9	0.21	0.17
35[2,4]	23	47	0.63	9	5.5	14	0.42	0.41
34	23	161	0.69	5	3.5	19	0.25	0.20
28B	14	50	0.69	4	10.5	3	0.09	0.07
DB3	17	126	0.70	5	4.5	6	0.18	0.12
MT1	18	149	0.73	7	10	3	0.06	0.05
DB5	14	217	0.74	4	8	3	0.06	0.04
33	20	175	0.76	7	5	8.5	0.19	0.11
I13[1]	13	213	0.7	6	18	10	0.08	0.06
30	16	220	0.77	4	6.5	5	0.14	0.09
DB6	15	196	0.74	4	9.7	13	0.20	0.13
BW1	12	98	0.73	4	10	5	0.09	0.06

$\Sigma^{210}Pb_{ex}$ (dpm cm^{-2})	$\Sigma^{137}Cs$ (dpm cm^{-2})	Comments
25.5±3.2	7.4±0.3	
21.6±1.3		^{137}Cs background not reached.
23.3±2.6	6.8±0.3	Mixed $^{210}Pb_{ex.}$ Adjusted according to ^{137}Cs onset.
36.7±1.5	9.6±0.2	Mixed core.
30.7±2.1	7.2±0.3	Adjusted according to onset of ^{137}Cs.
13.8±1.2	1.9±0.4	^{137}Cs in top 6 cm.
25.3±5.2	5.4±0.6	Adjusted according to onset of ^{137}Cs.
31.0±0.9	2.9±0.1	^{137}Cs deeper than predicted.
19.0±2.0	2.3±0.3	^{137}Cs deeper than predicted.
34.1±1.9	4.9±0.2	ω gives good fit to ^{137}Cs onset.
37.2±0.9	1.5±0.2	Low ^{137}Cs activity.
21.9±1.9	3.0±0.2	Wide range.
55.9±2.1	4.7±0.2	ω gives good fit to ^{137}Cs onset.
40.7±1.2	2.2±0.3	ω in agreement with ^{173}Cs.

Note: SML= surface mixed layer; Φ_{av}= average porosity below SML; C_0= $^{210}Pb_{ex}$ activity at the sediment-water interface; Kb_1= upper layer mixing rate (mixing below Kb_1, defined by Kb_2 (not shown), was 0.01 cm^2 y^{-1} for all cores); SR=sedimentation rate (95% confidence limits); MAR=mass accumulation rate (95% confidence limits); $\Sigma^{210}Pb_{ex}$ and $\Sigma^{137}Cs$ = sediment inventories ±propagated error. [1]The ^{210}Pb activities were determined by the alpha method; [2]Unable to validate core due to incomplete or uniform ^{137}Cs profile; [3]Background levels were not reached within the length of the core. [4] The sedimentation rate calculated from this core is likely underestimated because ^{210}Pb activities at depth were variable probably reflecting dilution from coarser grained particles

10.3 **Methylmercury**

Dietary survey methods

The dietary survey used for this study was organized in the following way:

Subsection A:	Local fish and marine mammals
Subsection B:	Store-bought Fish
Subsection C:	Other country foods
Recall periods:	24-hour 1-month 3-month
Survey phases:	Winter (survey conducted in February/March 2014) Spring (survey conducted in June 2014) Summer/Fall (survey conducted in September 2014)

In summary, for each of the food group categories listed above, participants were asked to recall the quantity and frequency of foods eaten over the three recall periods listed above. They were also asked how the food was prepared (e.g. boiled vs. smoked).

Winter Survey. This survey was timed to capture the foods eaten during the winter months (December, January and February). In February/March of 2014, seven Inuit Research Assistants conducted the dietary survey with 231 Inuit in Rigolet, North West River, Happy Valley-Goose Bay and Mud Lake. This represented a 10% random sample of the Inuit population.

Spring Survey. This survey was timed to capture the foods eaten during the spring months (April, May and June). This phase captured the ice fishing and seal hunting seasons. In June 2014, our goal was to conduct the dietary survey with the same 10% sample as in the Winter survey, and we achieved a rate of 62% returning participants (143 people). We also added hair sampling at this time, with a goal of obtaining samples from all consenting participants, and achieved the collection and analysis of 157 hair samples (representing 6.4% of the Inuit population). We also added a targeted group of high-seal consumers to this phase, considering that both the survey and the hair sample would capture the traditional seal hunt, and the most concentrated time of year for seal consumption (as determined by local knowledge). Seven Community Research Assistants were trained and hired for the Spring survey and sampling phase, which lasted approximately 5 weeks.

Summer/Fall Survey. This survey was timed to capture the foods eaten during the summer months (June, July and August), when the summer net-fishing season (salmon, trout), and fish consumption among Inuit is high. The bulk of the field work for the Human Health Risk Assessment took place in September of 2014, when the dietary survey was completed by approximately 89% of the Inuit residents of Rigolet, 64% of the Inuit residents of North West River, and 34% of the Inuit population in Happy Valley-Goose Bay/Mud Lake, for an approximate total of 1057 participants. This phase of the study took a total of 8 weeks, with two Inuit Community Research Assistants working in Rigolet, two in North West River and 20 in Happy Valley-Goose Bay/Mud Lake. Very good representative samples of each age and gender group were obtained. Tables 10.3 to 10.5 provide participation rates and sample sizes achieved in all three seasons. In the Winter phase, surveys were conducted on paper. An electronic survey (on tablets) developed for use in the Spring and Summer/Fall phases improved efficiency and aided greatly with participant recruitment.

Hair sampling methods

To cross-validate results of the food frequency questionnaire, all Spring and Summer/Fall survey participants were asked to provide hair samples for mercury analysis. Since methylmercury makes up the majority of total mercury in hair (80–90%), total mercury in hair is a reliable biomarker of methylmercury intake. Total mercury concentrations of the two-centimeter proximal end of hair samples were analyzed at Harvard School of Public Health mercury lab by thermal decomposition, amalgamation, and atomic absorption spectrophotometry [EPA method 7473; Milestone Direct Mercury Analyzer (Milestone Inc., Shelton, CT, USA) (U.S. EPA, 2007)].

Hair samples of sufficient quantity to be analyzed were provided by 157 individuals (of all ages, including children over 12 months) during the Spring survey, and by 499 individuals (again, of all ages) during the Summer/Fall survey. Eighty-five participants provided hair samples in both seasons. Samples were cut from the middle back of the head (where it will be less obvious), as close to the scalp as possible in order to catch the most recent exposure to mercury. Each sample was approximately 30 mm thick. With respect to hair mercury analysis, the samples obtained in the Spring phase represent an approximate 6% sample of the Lake Melville Inuit population and the samples obtained during the Summer/Fall phase represent 20% of the Lake Melville Inuit population.

Community engagement and Inuit knowledge integration

Survey and hair sampling work was carried out by a total of 28 local (26 Inuit) Research Assistants, who completed two days of training, and worked an approximate total of 1566 person-hours.

Community information sessions were held at the launch of the study in Rigolet, North West River and Happy Valley-Goose Bay. Additional community updates were provided through: 1) a pamphlet (English and Inuttitut) describing the research purpose and activities, including frequently asked question on the topic of mercury exposure; 2) a direct mail-out to June 2014 participants summarizing work to date and describing what to expect for fall survey/hair sampling activities; 3) frequent updates on social media, providing project updates. Posters circulated in all communities (English and Inuktitut). Media releases resulted in local and national coverage.

Focus group sessions were conducted with Community Research Advisory Committees in all Upper Lake Melville communities and Rigolet, to improve the development of the food frequency survey. Changes to survey and hair sampling dates and sample sizes were made based on knowledge and advice provided. Likewise, the addition of local terms to the survey, and the assistance that the Community Research Advisors provided the study team in understanding local nuances related to country foods, how they are eaten and where they are obtained were invaluable to making this project a success. Informal contact with Community Research Advisors also assisted with participant recruitment, local transportation and project promotion.

Table 10.3. Number of Food Frequency Surveys conducted (3-month, 1-month and 24-hour recall).

Survey Phase	*Total number of surveys*	*Sample description*
Winter 2014	231	10% random sample of Inuit population
Spring 2014	294	10% random sample of Inuit population, plus 30 targeted surveys of “high seal consumers”
Summer/Fall 2014	1057	43% of Inuit population

Table 10.4. Number of hair samples taken

Month	*Total number of hair samples*	*Sample description*
Winter 2014	0	
Spring 2014	157	6.4% random sample of Inuit population, plus 23 targeted hair samples from “high seal consumers”
Sum 2014	499	20% of Inuit population

Table 10.5. Number of participants and percentage of Inuit participants in brackets recruited for sampling by community

Community (Inuit population)	*Sampling phase*			*Season*			*Unique participants*
	Winter	*Spring*	*Summer*	*All seasons*	*Two Seasons*	*One Season*	
Happy Valley-Goose Bay/Mud Lake (1,984)	170 (9%)	200 (10%)	671 (34%)	97 (5%)	103 (5%)	543 (27%)	743 (37%)
North West River (247)	30 (12%)	34 (14%)	158 (64%)	15 (6%)	24 (10%)	128 (52%)	167 (68%)
Rigolet (258)	31 (12%)	43 (17%)	229 (89%)	27 (10%)	16 (6%)	190 (74%)	233 (90%)
Total (2,489)	231 (9%)	277 (11%)	1058 (43%)	139 (6%)	143 (6%)	861 (35%)	1,143 (46%)

Table 10.6. Community-based monitoring of river water

Sample	*Location*	*Frequency*	*Period*	*Sampled by*	*Analysis*
River water	Churchill River	30-days	April 2014–ongoing	M. Biasutti -Brown	Mercury, TSS, salinity
River water	North West River	Quarterly	April 2014–January 2015	D. McLean and J. Townley	Mercury, TSS, salinity
River water	Goose River	Quarterly	April 2014–January 2015	D. McLean and J. Townley	Mercury, TSS, salinity

Table 10.7. Community-based monitoring of fish

Sample	*Location*	*Date*	*No. of samples*	*Sampled By*	*Analysis*
Smelt	Churchill River	September 2014	7		MeHg
Brook trout	Lake Melville		20	Inuit residents of North West River and Rigolet	MeHg
Lake trout	Churchill River	June–July 2014	13		MeHg
Stickleback	Churchill River and Lake Melville	July–Sept 2014	30	Field Research Coordinator	MeHg
Salmon	Lake Melville (Rigolet area)	July 2014	3	Rigolet fishers	MeHg
Longnose sucker	Lake Melville (between NWR/ Rigolet	July–Aug 2014	20	Inuit fishers, North West River and Rigolet	MeHg
Whitefish	Lake Melville (between NWR/ Rigolet	July–Aug 2014	20	Inuit fishers, North West River and Rigolet	MeHg
Flatfish	Lake Melville (between NWR/ Rigolet	July–Aug 2014	20	Inuit fishers, North West River and Rigolet	MeHg
Pike	Churchill River	July–Aug 2014 August 2015	13	Inuit fishers, Happy Valley-Goose Bay	MeHg isotope
Arctic char	20 miles East of Rigolet	August 2015	10	Inuit fisher, Rigolet	MeHg
Atlantic cod	St. Lewis Bay	September 2014	5	Labrador fisher	MeHg isotope
Mussels	Rigolet and NWR areas	June 2015	10	Inuit hunter	MeHg
Miscellaneous river fish	Churchill River above Muskrat Falls	August 2015	10	Inuit fishers	MeHg isotope

Table 10.8. Community-based monitoring of seals

Sample	*Location*	*Date*	*No. of samples*	*Sampled by*	*Analysis*
Seal muscle, liver, blubber and lower jaw	Lake Melville, North West River area	April/May 2014	7	Inuit hunters	MeHg and age
Seal muscle, liver, blubber and lower jaw	Lake Melville, Rigolet area	April/May 2014	10	Inuit Hunters	MeHg and age
Seal muscle, liver, blubber and lower jaw	Lake Melville, North West River area	April/May 2015	9	Inuit hunters	MeHg and age
Seal muscle, liver, blubber and lower jaw	Lake Melville, Rigolet area	April/May 2015	10	Inuit hunters	MeHg and age

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