

183

DA18

Régularisation des crues du bassin  
versant du lac Kénogami  
Saguenay-Lac-Saint-Jean 6211-01-005

M. Lucotte · R. Schetagne · N. Thérien  
C. Langlois · A. Tremblay (Eds.)

# Mercury in the Biogeochemical Cycle



Natural Environments and Hydroelectric  
Reservoirs of Northern Québec



Springer

*Environmental Science*

---

Series editors: R. Allan · U. Förstner · W. Salomons

Marc Lucotte · Roger Schetagne · Normand Thérien  
Claude Langlois · Alain Tremblay (Eds.)

# Mercury in the Biogeochemical Cycle

Natural Environments and Hydroelectric Reservoirs  
of Northern Québec (Canada)

With 69 Figures and 46 Tables

**Springer**

*Berlin  
Heidelberg  
New York  
Barcelona  
Hong Kong  
London  
Milan  
Paris  
Singapore  
Tokyo*



**Springer**

## Editors

Dr. Mark Lucotte  
Université du Québec à Montréal  
C.P. 8888, Succursale Centre-ville  
Montréal, Québec, Canada  
H3C 3P8

Claude Langlois  
Environnement Canada  
105 McGill street, 4th floor  
Montréal, Québec, Canada  
H2Y 2E7

Roger Schetagne  
Hydro-Québec  
855 Ste-Catherines east, 18th floor  
Montréal, Québec, Canada  
H2L 4P5

Dr. Alain Tremblay  
Hydro-Québec  
855 Ste-Catherines east, 18th floor  
Montréal, Québec, Canada  
H2L 4P5

Dr. Normand Thérien  
Université de Sherbrooke  
Dept. of Chemical Engineering  
Faculty of Engineering  
Sherbrooke, Québec, Canada  
J1K 2R1

ISBN 3-540-65755-X Springer-Verlag Berlin Heidelberg New York

CIP data applied for

Die Deutsche Bibliothek - CIP-Einheitsaufnahme  
Mercury in the biogeochemical cycle : natural environments and hydroelectric reservoirs of northern Québec (Canada) ; with 46 tables / Marc Lucotte ... (ed.). - Berlin ; Heidelberg ; New York ; Barcelona ; Hong Kong ; London ; Milan ; Paris ; Singapore ; Tokyo : Springer, 1999  
(Environmental science)  
ISBN 3-540-65755-X

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in other ways, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution act under German Copyright Law.

© Springer-Verlag Berlin Heidelberg 1999  
Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: Camera-ready by editors  
Cover layout: Struve & Partner, Heidelberg  
SPIN: 10706080 32 / 3020 - 5 4 3 2 1 0 - Printed on acid-free paper

## Foreword

Nowadays, major environmental issues are the object of large public debates despite the fact that scientific knowledge is often insufficient to draw unequivocal conclusions. Such is the case in the ongoing debate regarding the specific contributions of anthropogenic greenhouse gas emissions and of natural climate changes to global warming. At least 10 to 20 years of additional observations will be required, before we will be able to conclude, with certainty, on this subject. In the mean time, and as directed by their immediate interests, people will continue to promote contradictory opinions. The media are, in part, responsible for perpetuating such debates in that they convey indiscriminately the opinion of highly credible scientists as that of dogmatic researchers, the latter, unfortunately too often expressing working hypotheses as established facts. Naturally, in a similarly misinformed manner, pressure groups tend to support the researcher whose opinions most closely represent either their particular ideological battles or their economic interests and, hence, in their own way, add further to the confusion and obscurity of the debate.

Only a few years ago, mercury (Hg)contamination in hydroelectric reservoirs was the object of such media and social biases. At the time, analytical data used to support the discourse were themselves uncertain and numerous hypotheses, often times fanciful, were proposed and hastily "delivered" to the public. Thankfully, in this case, the scientific progress of the past decade has made it possible to present now a dispassionate view of the question and, hence, to address the issue without its former irrational aspects. The review that follows falls within the scope of such a perspective. It presents an exhaustive review of what is known about the biogeochemical cycling of Hg in hydroelectric reservoirs as well as in natural aquatic systems of the boreal forest region of northern Québec. This work constitutes the North American counterpart to a parallel publication by Scandinavian researchers. The convergence of both studies permits the drawing of important conclusions.

Indeed, the food chain of numerous aquatic ecosystems is contaminated by Hg. The contamination can even reach, in certain organisms, such as predatory fish and aquatic mammals, levels that exceed those prescribed by governmental agencies. This contamination is unfortunately already widespread in natural lakes, but it is particularly noticeable in hydroelectric reservoirs during the first few decades following their impoundment. With respect to natural lakes, the role of increasing anthropogenic Hg emissions cannot be ignored. The present study clearly shows

that the atmospheric fluxes of this metal have increased by a factor of three over the past century. In the second case, i.e., that of hydroelectric reservoirs, the extensive flooding of soils, whose various horizons accumulate both natural and anthropogenic heavy metal pollutants, also plays a critical role. In either case, the stimulation of bacterial activity by the availability of organic matter appears to be a determining factor. In fact, the availability of organic matter is the key to the bacterial processes leading to the methylation of Hg, that is, to its transformation from its inorganic state (essentially nontoxic) to an organo-metallic form that readily bioaccumulates in the food chain.

The various chapters of this volume represent benchmark contributions not only for a better understanding of the biogeochemical cycling of Hg but also, more generally, for a better management of the associated social issues. From a practical point of view, one can conclude with some relief that the enhanced Hg contamination of hydroelectric reservoirs subsides in a period of, at most, only a few decades, and that during this transitory period Hg levels in a number of the fishery resources remain below tolerable limits. Unfortunately, the long term contamination of aquatic systems, be they natural or developed, as a consequence of increasing atmospheric contaminant fluxes, remains disconcerting and will demand action on an international scale to be rectified.

Nevertheless, the following work will constitute an important reference in the scientific literature for many years. It is exhaustive, scholarly, solidly supported, and marks the conclusion of a university-industry collaborative effort initiated nearly ten years ago, under the aegis of the Hydro-Québec-Université du Québec à Montréal *Chaire de recherche en environnement*, with the support of the National Science and Engineering Research Council of Canada and the collaboration of the Université de Sherbrooke and the Canadian Wildlife Service. The findings presented in this volume are the outcome of an exemplary collaboration between university researchers and Hydro-Québec scientists. Many findings central to this work were successfully concluded and sanctioned in the form of Master's and Ph.D. theses, all of which constitute important annexes in support of the present document. The reader who wishes to get deeper insights about given aspects of the biogeochemistry of Hg, may refer to these complementary works. However, as it is, the present volume is detailed enough to provide answers to most questions one could have about the Hg contamination of the boreal forest domain of Québec.

Claude Hillaire-Marcel  
Titulaire de la Chaire de recherche en environnement  
Hydro-Québec-CRSNG-UQAM

## Contents

<b>Résumé et synthèse (French summary)</b> .....	1
<b>1 Introduction</b> .....	23
1.1 The Mercury Issue in Northern Québec .....	23
1.2 Geographic Setting .....	24
1.2.1 Drainage Basin and Relief.....	24
1.2.2 Climate and Hydrology .....	25
1.2.3 Vegetation and Wildlife .....	26
1.2.4 Water Quality and Fish .....	26
1.2.5 Human Settlements .....	27
1.3 Hydroelectric Developments .....	27
1.3.1 Reservoirs.....	27
1.3.2 Other Modified Environments .....	31
1.4 Evolution of the Biophysical Environment .....	31
1.4.1 Water Quality .....	32
1.4.2 Plankton and Benthos.....	32
1.4.3 Fish.....	32
1.5 Contents and Rationale.....	35
<b>2 Analysis of Total Mercury and Methylmercury in Environmental Samples</b> .....	41
Abstract .....	41
2.1 Introduction .....	41
2.2 Total Mercury Measurements.....	42
2.2.1 Total Mercury by Cold Vapor Atomic Absorption Spectrophotometry .....	42
2.2.1.1 Organisms and Sediment Samples .....	42
2.2.1.2 Water Samples .....	43
2.2.2 Total Mercury by Atomic Fluorescence Spectrophotometry .....	44
2.2.2.1 Organisms and Sediment Samples .....	45
2.2.2.2 Water Samples .....	45



2.3 Methylmercury Measurements .....	48
2.3.1 Organisms and Sediment Samples .....	49
2.3.2 Water Samples .....	50
2.4 Conclusions .....	51
Acknowledgements .....	52
<b>Mercury and Methylmercury in Natural Ecosystems of Northern Québec</b>	
<b>3 Mercury in Natural Lakes and Unperturbed Terrestrial Ecosystems of Northern Québec .....</b>	<b>55</b>
Abstract .....	55
3.1 Introduction .....	56
3.2 Materials and Methods .....	57
3.2.1 Aquatic Systems .....	57
3.2.2 Terrestrial Systems .....	58
3.2.3 Analyses .....	58
3.3 Results and Discussion .....	59
3.3.1 Mercury in Natural Lakes of Northern Québec .....	59
3.3.1.1 Presence and Diagenesis of Mercury in Lake Sediments .....	59
3.3.1.2 Historic Interpretation of the Presence of Mercury in Sediments .....	61
3.3.1.3 Sedimentary Mercury and Terrigenous Organic Matter .....	62
3.3.1.4 Mercury in the Water Column of Natural Lakes .....	62
3.3.1.5 Mercury in Aquatic Macrophytes and in Riparian Plants .....	66
3.3.2 Mercury in Terrestrial Systems of Northern Québec .....	67
3.3.2.1 Mercury in Terrestrial Vegetation of Northern Québec .....	69
3.3.2.2 Distribution of Mercury in Forest Soils and Peatlands of the Boreal Domain .....	72
3.3.2.3 Anthropogenic Fraction of Mercury in Soils of Northern Québec .....	77
3.3.3 Patterns of Atmospheric Mercury Deposition throughout Northern Québec .....	81
3.4 Conclusions .....	85
Acknowledgements .....	86

<b>4 Bioaccumulation of Mercury and Methylmercury in Invertebrates from Natural Boreal Lakes .....</b>	<b>89</b>
Abstract .....	89
4.1 Introduction .....	89
4.2 Materials and Methods .....	90
4.2.1 Study Areas .....	90
4.2.2 Sampling .....	93
4.2.2.1 Insects .....	93
4.2.2.2 Plankton .....	93
4.2.3 Analyses .....	94
4.3 Results and Discussion .....	94
4.3.1 Total Mercury and Methylmercury Concentrations in Invertebrates .....	94
4.3.2 Bioavailability of Total Mercury and Methylmercury for Insect Larvae .....	101
4.3.3 Environmental Factors Influencing Mercury Bioavailability .....	102
4.3.4 Biomagnification of Methylmercury along the Food Web .....	104
4.3.5 Diversity, Biomass and Mercury Burdens .....	109
4.4 Conclusions .....	112
Acknowledgements .....	112
<b>5 Mercury in Fish of Natural Lakes of Northern Québec .....</b>	<b>115</b>
Abstract .....	115
5.1 Introduction .....	115
5.1.1 Study Area .....	116
5.2 Materials and Methods .....	120
5.3 Results .....	121
5.4 Discussion .....	125
5.5 Conclusions .....	129
Acknowledgements .....	130
<b>6 Mercury in Birds and Mammals .....</b>	<b>131</b>
Abstract .....	131
6.1 Introduction .....	131
6.2 Study Area .....	132
6.3 Materials and Methods .....	133
6.4 Results and Discussion .....	134
6.4.1 Mercury in Birds .....	134
6.4.2 Relationship with Geographical and Habitat Distribution .....	138
6.4.3 Diet Types .....	138

6.4.4	Eggs .....	140
6.4.5	Terrestrial Mammals .....	141
6.4.6	Marine Mammals .....	142
6.4.7	Freshwater Seals .....	143
6.5	Conclusions .....	144
	Acknowledgements .....	144

## Mercury Dynamics at the Flooded Soil-Water Interface in the Reservoirs

<b>In Vitro Release of Mercury and Methylmercury from Flooded Organic Matter .....</b>	<b>147</b>
Abstract .....	147
7.1 Introduction .....	147
7.2 Materials and Methods .....	149
7.2.1 Sample Collection .....	149
7.2.2 Experimental Set up .....	149
7.2.3 Analytical Methods .....	151
7.2.3.1 Total Hg .....	151
7.2.3.2 MeHg .....	152
7.3 Results .....	152
7.4 Discussion .....	154
7.5 Conclusions .....	163
Acknowledgements .....	164
<b>8 Mercury Dynamics at the Flooded Soil-Water Interface in Reservoirs of Northern Québec: in Situ Observations .....</b>	<b>165</b>
Abstract .....	165
8.1 Introduction .....	166
8.2 Materials and Methods .....	167
8.2.1 Study Sites .....	167
8.2.2 Sampling .....	167
8.2.3 Analyses .....	169
8.3 Results and Discussion .....	170
8.3.1 Temporal Evolution of Mercury in Flooded Soils .....	170
8.3.2 Mercury in the Water Column of Flooded Systems .....	176
8.3.2.1 Dissolved Fraction .....	176
8.3.2.2 Particulate Fraction .....	180

8.3.3	Influence of Flooded Soils on the Biogeochemical Cycle of Mercury in Reservoirs .....	183
8.3.3.1	Diffusion of Mercury from Flooded Soils .....	183
8.3.3.2	Burrowing Organisms and Erosion .....	184
8.3.3.3	Enhanced Biological Production and Methylation of Mercury .....	184
8.4	Conclusions .....	186
	Acknowledgements .....	189

## Evolution of Mercury Concentrations in Aquatic Organisms from Hydroelectric Reservoirs

<b>9 Bioaccumulation of Methylmercury in Invertebrates from Boreal Hydroelectric Reservoirs .....</b>	<b>193</b>
Abstract .....	193
9.1 Introduction .....	193
9.2 Materials and Methods .....	194
9.2.1 Study Area .....	194
9.2.2 Sampling .....	194
9.2.2.1 Insects .....	194
9.2.2.2 Plankton .....	198
9.2.2.3 Flooded Soils and Lake Sediments .....	199
9.2.3 Analysis .....	199
9.3 Results and Discussion .....	199
9.3.1 Methylmercury Concentrations in Invertebrates .....	199
9.3.2 Biomagnification of Methylmercury Along the Invertebrate Food Chain .....	202
9.3.3 Bioavailability of Methylmercury to Insects .....	205
9.3.4 Bioavailability of Methylmercury to Plankton .....	208
9.3.5 Biomass and MeHg Burdens .....	210
9.4 Conclusions .....	213
Acknowledgements .....	214
<b>10 Mercury Accumulation in Fish from the La Grande Complex: Influence of Feeding Habits and Concentrations of Mercury in Ingested Prey .....</b>	<b>215</b>
Abstract .....	215
10.1 Introduction .....	215
10.2 Materials and Methods .....	216

Contents

10.3 Results and Discussion .....	222
10.3.1 Non-Piscivorous Fish .....	222
10.3.2 Piscivorous Fish .....	227
10.4 Conclusions .....	232
Acknowledgements .....	233
<b>Post-impoundment Evolution of Fish Mercury Levels at the La Grande Complex, Québec, Canada (from 1978 to 1996) .....</b>	<b>235</b>
Abstract .....	235
11.1 Introduction .....	236
11.2 Materials and Methods .....	236
11.3 Results .....	238
11.3.1 Reservoirs .....	238
11.3.2 Dwarf Lake Whitefish .....	243
11.3.3 Rivers with Reduced Flow .....	243
11.3.4 Diversion Routes .....	243
11.3.5 Downstream from Reservoirs .....	245
11.3.5.1 The Caniapiscou River .....	245
11.3.5.2 The La Grande River .....	247
11.3.5.3 The Coast of James Bay .....	248
11.4 Discussion .....	249
11.4.1 Reservoirs .....	249
11.4.1.1 Increases of Fish Mercury Levels in Reservoirs .....	249
11.4.1.2 Factors Explaining Differences Observed Between Reservoirs .....	250
11.4.1.3 Duration of the Phenomenon in Reservoirs .....	254
11.4.2 Downstream from Reservoirs .....	257
11.4.3 Rivers with Reduced Flow .....	257
11.5 Conclusions .....	258
Acknowledgements .....	258
<b>12 Calculated Fluxes of Mercury to Fish in the Robert-Bourassa Reservoir .....</b>	<b>259</b>
Abstract .....	259
12.1 Introduction .....	259
12.2 Materials and Methods .....	261
12.2.1 Estimation of Fish Standing Stocks .....	261
12.2.2 Estimation of Biomass Fluxes .....	261
12.2.3 Estimation of Hg Fluxes .....	263
12.2.4 Calculation of Hg Fluxes from Vegetation .....	264
12.2.5 Resolution of the Major Hg Fluxes .....	264

12.3 Results and Discussion .....	265
12.3.1 Biomass and Hg Fluxes .....	265
12.3.2 Fluxes of Hg from Vegetation .....	267
12.3.3 Resolution of the Major Mercury Fluxes .....	268
12.4 Conclusions .....	271
Acknowledgements .....	272

**Mercury Toxicity for Wildlife Resources**

<b>13 Assessment of the Ecotoxic Risk of Methylmercury Exposure in Mink (<i>Mustela vison</i>) Inhabiting Northern Québec .....</b>	<b>275</b>
Abstract .....	275
13.1 Introduction .....	275
13.2 Materials and Methods .....	276
13.3 Results and Discussion .....	277
13.3.1 <i>In vitro</i> Exposure to Methylmercury .....	277
13.3.2 Mercury Concentrations in Tissues Observed in the Wild .....	279
13.3.3 Ecological, Biological and Ethological Determinants .....	282
13.3.4 Risk to Wild Mink .....	283
13.4 Conclusions .....	285
Acknowledgements .....	285
<b>14 Breeding Success of Osprey under High Seasonal Methylmercury Exposure .....</b>	<b>287</b>
Abstract .....	287
14.1 Introduction .....	287
14.2 Study Area and Methods .....	288
14.3 Results .....	289
14.4 Discussion .....	291
14.5 Conclusions .....	292
Acknowledgements .....	293
<b>15 Synthesis .....</b>	<b>295</b>
15.1 Mercury in Natural Ecosystems of Northern Québec .....	295
15.1.1 Sources of Mercury .....	295
15.1.2 Sediments and the Water Column .....	296
15.1.3 Invertebrates .....	296
15.1.4 Fish .....	297



15.1.5 Aquatic Birds .....	298
15.1.6 Mammals.....	298
15.2 The Mercury Issue at the La Grande Hydroelectric Development Complex .....	299
15.2.1 Methylation and Passive Transfer from the Flooded Soils and Vegetation to the Water Column .....	300
15.2.2 Mercury Increases in Organisms at the Base of the Aquatic Food Chain .....	302
15.2.3 Additional Active Transfer from the Flooded Soils to the Aquatic Food Chain .....	303
15.2.4 Mercury Increases in Fish .....	304
15.2.4.1 Reservoirs .....	304
15.2.4.2 Downstream from Reservoirs .....	305
15.2.5 Duration of Increased Mercury Levels in Fish.....	305
15.2.5.1 Degradation of Terrigenous Organic Matter and Release of Nutrients.....	306
15.2.5.2 Erosion.....	306
15.2.5.3 Active Transfer from Burrowing Insects and Periphyton.....	307
15.2.6 Morphological and Hydrologic Factors Influencing the Evolution of Mercury Levels in Fish in Reservoirs .....	307
15.2.6.1 Land Area Flooded to Annual Volume of Water Ratio.....	308
15.2.6.2 Flooded Land Area in Drawdown Zone .....	308
15.2.6.3 Filling Time .....	309
15.2.7 Risk to Wildlife.....	309
15.2.7.1 Mink Experiment.....	309
15.2.7.2 Breeding Success of Osprey .....	310
<b>16 Conclusion and Prospects .....</b>	<b>313</b>
16.1 Development of Models Predicting Fish Mercury Levels in Reservoirs.....	314
16.2 Potential Mitigation Measures to Reduce the Temporary Increase in Fish Mercury Levels.....	315
16.3 Environmental Risk.....	316
<b>References .....</b>	<b>317</b>