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The chemistry and transport of mercury in a small wetland in the Adirondack region of New York, USA

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Abstract. The biogeochemistry of Hg was evaluated in a small wetland in the Adirondack region of New York. Concentrations of total Hg (Hg_T) in streamwater draining the wetland showed little temporal variation. The annual areal watershed flux of Hg_T (2.2 $\mu g/m^2$-yr) was considerably smaller than regional inputs of atmospheric deposition of Hg_T, indicating that the terrestrial environment is a net sink for atmospheric deposition of Hg_T. Drainage inputs of Hg_T were conservatively transported through the beaver impoundment. The annual flux of total methylmercury ($CH_3Hg_T^+$) was greater than literature values of atmospheric deposition suggesting that the watershed is a net source of $CH_3Hg_T^+$. Stream concentrations of $CH_3Hg_T^+$ increased during low-flow summer conditions in a riparian wetland, and particularly at the outlet of the beaver impoundment. Net production of $CH_3Hg_T^+$ occurred in the beaver impoundment (0.45 $\mu g/m^2$-yr). Rates of net methylation for the beaver impoundment were comparable to values reported in the literature for wetlands.

Introduction

Mercury (Hg) is a toxic trace metal and has been linked to human illness and environmental damage. It appears that industrial activities have resulted in substantial emissions of Hg to the atmosphere and long-distance transport (Engstrom et al. 1994; Mason et al. 1995; Hudson et al. 1995). Atmospheric emissions have apparently caused widespread contamination of Hg in aquatic environments, and elevated concentrations in biota (Zillioux et al. 1993). In the U.S., the principal anthropogenic sources of Hg include coal-fired power plants, municipal and medical waste incinerators, and commercial/industrial boilers, which together contribute nearly 98% of the total anthropogenic emissions of Hg to the atmosphere (EPRI 1994).

The mechanisms and rates of the supply of methylmercury (CH_3Hg^+) to lakes and ultimately to fish is a critical uncertainty in assessments of the effects

of atmospheric deposition of Hg (EPRI 1994; Rudd 1995). Although small amounts of CH_3Hg^+ enter ecosystems by atmospheric deposition (Fitzgerald et al. 1991; Lee & Iverfeldt 1991; St. Louis et al. 1994), there is increasing evidence that CH_3Hg^+ supply from wetlands is due to internal methylation of ionic Hg (Hg_T^{2+}; St. Louis et al. 1994; Bishop et al. 1995; Krabbenhoft et al. 1995). Concentrations of CH_3Hg^+ increase in waters draining wetlands (Krabbenhoft et al. 1995; Branfireun et al. 1996). Large increases in CH_3Hg^+ also occur when upland watersheds are flooded (Hecky et al. 1991; Rudd 1995). Previous studies of lakes in the Adirondack region of New York indicate that wetlands have a critical role in the transport, cycling and bioavailability of Hg (Driscoll et al. 1994, 1995). Concentrations of total Hg (Hg_T) and $CH_3Hg_T^+$ in lakewater were strongly related to concentrations of dissolved organic carbon (DOC). Lakewater DOC appeared to be largely controlled by the fraction of this catchment that is wetlands. In addition, organic acids produced in wetlands complex both Hg_T^{2+} and $CH_3Hg_T^+$, decreasing the bioavailablity of these species (Driscoll et al. 1994).

The objective of this study was to evaluate concentrations and fluxes of Hg_T and $CH_3Hg_T^+$ in streamwaters draining a small wetland in the Adirondack region of New York.

Methods and site description

The northern hardwood forest landscape of the northeastern U.S. contains a relatively small area of wetlands (usually $<$ 10% of the landscape), but these wetlands appear to be important in regulating the supply of $CH_3Hg_T^+$ to surface water (St Louis et al. 1994). Wetlands are distributed across the glaciated landscapes of North America in a discontinuous complex mosaic. Two of the most common wetland types are riparian wetlands and wetlands created by beaver impoundments. Riparian wetlands usually occupy the 5–10 m wide zone adjacent to first and second order streams in northern forests and are often dominated by alders (*Alnus* sp.) and herbs. Beavers (*Castor canadensis*) build dams across streams; hence, most of the beaver ponds in northern forests develop over riparian wetlands. Our study site at Pancake-Hall Creek (43°50′N, 74°52′W) was selected because of the presence of a riparian wetland and a beaver impoundment within the drainage basin.

Pancake-Hall Creek is located in the Big Moose drainage basin in the Adirondack region of New York (Figure 1). The morphometry and basin characteristics of Pancake-Hall Creek are similar to other headwater streams in the Adirondacks impacted by beaver (Cirmo & Driscoll 1993). The beaver pond associated with this stream has a major perennial second-order inlet and several ephemeral inlets along its western and northern edges. The pond has

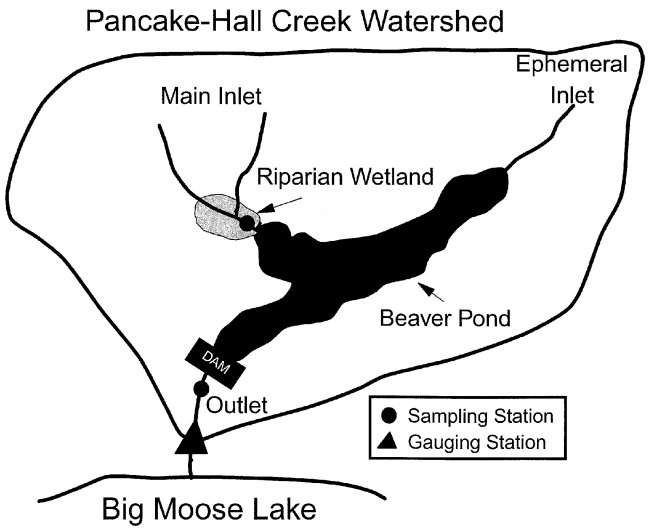

Figure 1. Location of Pancake-Hall Creek Watershed, gauging station and water sampling sites.

a volume of 12,500 m^3, a surface area of 30,000 m^2 and a mean depth of 0.4 m. Hydrologic discharge through the wetland is highly seasonal, with high flow occurring during late fall and spring. Low flow conditions are typically evident during winter and summer. The hydrologic gauging station for this site includes a flume to accommodate relatively high flow conditions and a V-notch weir for low flow conditions. A detailed description of the hydrology and biogeochemistry of Pancake-Hall Creek is given by Cirmo and Driscoll (1993).

The catchment is primarily a second-growth deciduous forest. Major tree species include American beech (*Fagus grandifolia* Ehrh.), yellow birch *(Betula alleghaniensis* Britton), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), and red spruce (*Picea rubens* Sarg.). Balsam fir (*Abies balsamea* (L.) Mill.) and hemlock (*Tsuga canadensis* (L.) Carr.) are evident along the shoreline and in saturated zones adjacent to the pond. The shallow area near the inlet to the pond is dominated by sedges (*Carex* sp.) and mosses (*Sphagnum* sp.). The sediments are organic and peaty, and covered with *Sphagnum* in shallow zones.

To investigate temporal patterns in the chemistry of Hg at Pancake-Hall Creek, water samples were collected at the major inlet (riparian wetland) and outlet of the beaver impoundment from October 1993 to April 1995 (Figure 1). Clean techniques were used in all phases of sample collection and handling. Streamwater was collected into 1 L Teflon bottles for Hg analysis, and into 1 L polypropylene bottles for the analysis of major solutes. Bottles were

opened and closed beneath the water surface during sample collection. Each bottle was rinsed three times with water prior to collecting the final sample. The bottles were hermetically sealed and double-bagged immediately after sample collection.

For analysis of Hg_T, samples were first oxidized with BrCl. After oxidation, $NH_2OH{\cdot}HCl$ was used to reduce excess BrCl. Samples were then reduced with $SnCl_2$, purged to Au traps, and thermally desorbed as Hg^0 with He carrier gas for detection by cold vapor atomic fluorescence spectrometry (CVAFS). Total CH_3Hg^+ was processed by first extracting samples from a HCl/KCl matrix into CH_2Cl_2 followed by back extraction into pure water (by solvent evaporation). Determination of $CH_3Hg^+_T$ was accomplished by aqueous phase ethylation with $NaB(C_2H_5)_4$, cryogenic gas chromatograph separation and CVAFS detection. Details of the procedure used to fractionate aqueous samples for Hg are provided by Bloom (1989). Water samples collected were also measured for concentrations of major solutes using the procedures summarized in Driscoll and van Dreason (1993). All chemical analyses were conducted at Syracuse University. Solute mass balance calculations for the wetland were calculated from 1 March 1994 to 1 March 1995 using the approach described by Cirmo and Driscoll (1993).

Results and discussion

The time-series of water chemistry at Pancake-Hall Creek showed remarkably constant concentrations of Hg_T throughout the study period (Figure 2). The mean concentrations ($\pm$ standard deviation) of Hg_T was 2.3 ($\pm$ 0.26) ng/L in the inlet stream and 2.5 ($\pm$ 0.22) ng/L in the outlet to the beaver impoundment. This relatively small variation in concentrations is surprising in view of the large changes in discharge that occurred over the annual cycle. Given the strong relationship between concentration of Hg_T and DOC in Adirondack lakes (Driscoll et al. 1995), we anticipated concentrations of Hg_T to follow temporal variations in DOC at Pancake-Hall Creek. The inlet stream showed little temporal variation in concentrations of DOC (and Hg_T), with the exception of a high concentration in July (7.6 mg C/L). Pond outflow, however, exhibited marked increases in DOC during the summer period, with no corresponding increase in Hg_T.

In contrast to Hg_T, concentrations of $CH_3Hg^+_T$ showed seasonal variations. Concentrations of $CH_3Hg^+_T$ were relatively low in October when monitoring was initiated, increased during the summer in both the inlet and outlet waters, decreased in the early fall and remained relatively constant through the winter. Concentrations of $CH_3Hg^+_T$ were consistently higher in the outlet of the beaver impoundment than the inlet stream draining the riparian

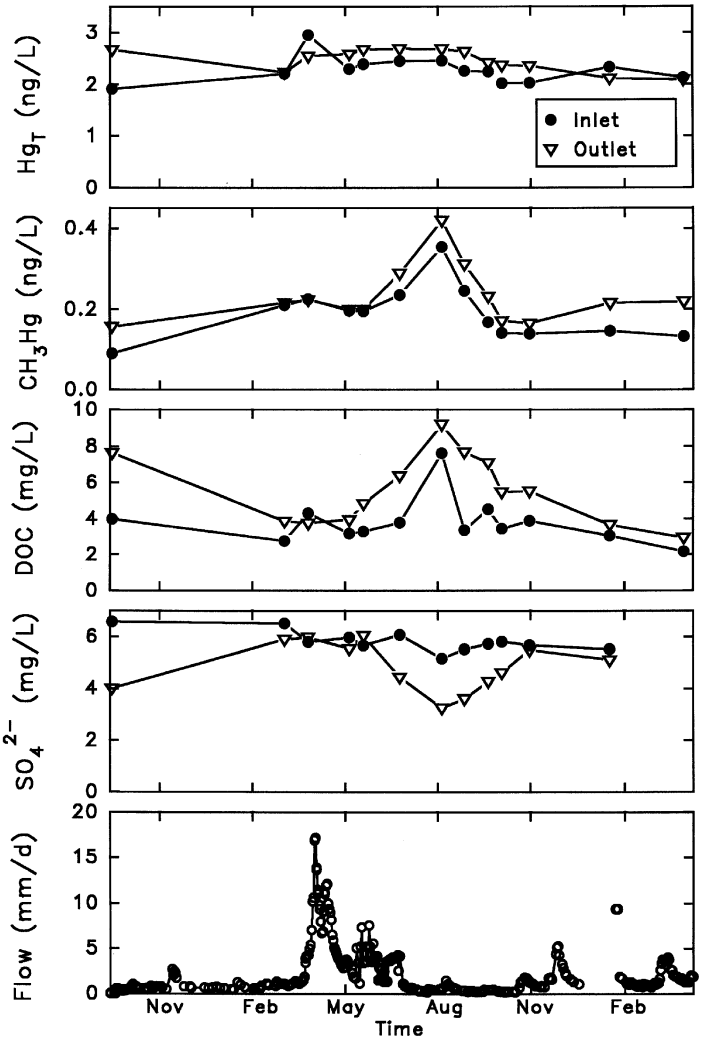

Figure 2. Time-series of concentrations of Hg_T, $CH_3Hg_T^+$, DOC and SO_4^{2-}, and discharge for streamwaters draining the riparian wetland (inlet to the beaver impoundment) and the beaver pond at Pancake-Hall Creek.

wetland. Only during the high flow spring period were concentrations of $CH_3Hg_T^+$ similar in the inlet and outlet waters. The magnitude of the summer increase in $CH_3Hg_T^+$ was greater in the outflow of the beaver impoundment than the inlet stream. The increase in $CH_3Hg_T^+$ concentrations in the pond outflow was coincident with a depletion in concentrations of SO_4^{2-} in the outlet waters during the summer compared to inlet concentrations. We observed

an increase in the percentage of Hg_T as $CH_3Hg_T^+$: from 6 to 10% during the fall/winter/spring to 16% during summer. These patterns are expected because methylation of Hg is largely mediated by SO_4^{2-} reducing bacteria (Gilmour et al. 1992) and the percent of Hg_T occurring as $CH_3Hg_T^+$ increases under reducing conditions (Driscoll et al. 1994). The small increase in concentrations of $CH_3Hg_T^+$ in the inlet stream during summer suggests that the riparian wetland may also be an environment for Hg methylation. Subtle decreases in SO_4^{2-} and increases DOC concentrations in the inlet stream during the low flow summer conditions may be suggestive of reducing conditions in the riparian wetland. In contrast to concentrations of Hg_T, concentrations of $CH_3Hg_T^+$ were correlated with concentrations of DOC, ($CH_3Hg_T^+$(ng/L) = 0.025*DOC (mg C/L) + 0.10, $r^2 = 0.41$). Summer increases in concentrations of $CH_3Hg_T^+$ coincided with increases in DOC, particularly for the outflow of the beaver impoundment. It is unclear if the correlation between $CH_3Hg_T^+$ and DOC is causal (i.e., due to organic complexation of $CH_3Hg_T^+$) or due to the increased production of both solutes in the beaver impoundment during summer. However, these observations illustrate the importance of wetlands in regulating Hg_T and $CH_3Hg_T^+$ fluxes in this ecosystem and ultimately the supply to the downstream lake (i.e., Big Moose Lake), and are consistent with the findings of Bishop et al. (1995) and Krabbenhoft et al. (1995) in Sweden and Wisconsin, respectively.

Annual watershed areal fluxes of Hg_T for the inflow and outflow from the beaver impoundment were 2.2 $\mu g/m^2$-yr at both sites. This terrestrial flux of Hg_T was in the upper part of the range of values reported for remote watersheds (Table 1). The similar fluxes of Hg_T for drainage from the riparian wetland and the outflow of the beaver impoundment indicate that inputs of Hg_T were largely transported through the pond. This apparently steady-state transport of Hg_T may reflect the older age of the impoundment ($>$ 10 yr.). Pond sediments do not appear to be an important source of Hg_T. Rather, drainage inflow seems to be the major input of Hg_T to the pond. If these watershed areal fluxes are compared to estimates of atmospheric deposition of Hg_T from Lake Champlain (9 $\mu g/m^2$-yr; Burke et al. 1995), it appears that the terrestrial environment is a sink for atmospheric deposition of Hg_T.

The annual watershed flux of $CH_3Hg_T^+$ from the upland/riparian wetland was 0.17 g/m^2-yr. This value is high in comparison to other watershed studies, and similar to values reported by St. Louis et al. (1994) for wetland drainage in Ontario (Table 1). Unfortunately, measurements of atmospheric deposition of $CH_3Hg_T^+$ are not available for the study site or the region. Fitzgerald et al. (1991) measured wet deposition of $CH_3Hg_T^+$ at Wisconsin obtaining a value of 0.09 $\mu g/m^2$-yr. The range of $CH_3Hg_T^+$ reported for wet/bulk deposition in the literature is 0.04–0.4 $\mu g/m^2$-yr (St. Louis et al. 1995; Hultberg et al.

Table 1. Comparison of watershed fluxes of Hg_T and $CH_3Hg_T^+$ obtained in this study with values reported in the literature (in $\mu g/m^2$-yr).

Location	Hg_T Flux	$CH_3Hg_T^+$ Flux	Reference
Sweden	0.8–5.9		Johansson et al. (1991)
Southern Sweden	2.3–3.5	0.12	Lee and Hultberg (1990)
Northern Sweden	1.2–1.8	0.08–0.16	Lee et al. (1995)
Wisconsin	0.8	0.06–0.15	Krabbenhoft et al. (1995)
Ontario	0.6–2.1		Mierle and Ingram (1991)
Ontario upland	0.3–2.3	0.007–0.098	St. Louis et al. (1994)
Ontario wetland		0.18–0.55	St. Louis et al. (1994)
New York	2.2	0.17	this study

1994). Hultberg et al. (1994) and St. Louis et al. (1994) have reported that upland watersheds are sinks for atmospheric deposition of $CH_3Hg_T^+$. Because atmospheric deposition of $CH_3Hg_T^+$ is well in excess of drainage losses, it seems likely that the upland/riparian wetland portion of the Pancake-Hall Creek Watershed is a net source of $CH_3Hg_T^+$. Based on these studies of upland watersheds, the riparian wetland of Pancake-Hall Creek watershed is likely an important area of $CH_3Hg_T^+$ production. The annual watershed areal flux of $CH_3Hg_T^+$ was greater in the outflow (0.20 $\mu g/m^2$-yr) than entering the beaver impoundment (0.17 $\mu g/m^2$-yr), indicating that net production of $CH_3Hg_T^+$ occurs within the pond (0.45 $\mu g/m^2$-yr based on the pond surface area). Drainage inputs of Hg_T were probably methylated within the beaver impoundment. Rates of in-pond methylation, DOC production and SO_4^{2-} reduction were greatest during the summer, coinciding with conditions of maximum temperature, anoxia and hydraulic residence time in the beaver impoundment (Cirmo & Driscoll 1993). The areal rate of $CH_3Hg_T^+$ production for the beaver impoundment is comparable to rates reported for wetlands (0.3 $\mu g/m^2$-yr), at the low end of the range reported for lakes (0.5–3 $\mu g/m^2$-yr) and well below values reported for flooded terrestrial areas (13 $\mu g/m^2$-yr; Rudd 1995). A critical question regarding the supply of $CH_3Hg_T^+$ to downstream lakes is whether beaver impoundments function as wetlands or recently flooded terrestrial environments. Based on rates of $CH_3Hg_T^+$ production, it appears that net $CH_3Hg_T^+$ production in this older beaver impoundment is more comparable to a wetland than a recently flooded terrestrial area. However, over the lifetime of a beaver impoundment it seems likely that rates of net $CH_3Hg_T^+$ production would be initially high, in response to flooding, and decline with time as the impoundment approaches steady-state with respect to Hg_T inputs.

Changes in land-use and anthropogenic disturbance (e.g., forest cutting and regrowth, acidification from atmospheric deposition) may alter the transport, fate and bioavailablity of Hg. It seems plausible that changes in the distribution and abundance of wetland area and, in particular, beaver ponds may contribute to the supply of $CH_3Hg^+_T$ to Adirondack drainage lakes. As described above, wetlands are an important landscape position for CH_3Hg^+ formation. Our biogeochemical studies of beaver impoundments in the Adirondacks (Driscoll et al. 1987a; Cirmo & Driscoll 1993; Cirmo & Driscoll 1996) have shown that these systems greatly enhance the supply of DOC to downstream surface waters. Transport of Hg_T and CH_3Hg^+ are strongly linked to transport of DOC (Driscoll et al. 1995). In the northeastern U.S., the distribution and abundance of wetlands has varied through time. Agents such as beaver are responsible for establishing an ontogeny of ponds and wetlands from creation to maturation to decline. It seems likely that the production of $CH_3Hg^+_T$ and supply to surface waters will vary over the life-history of beaver ponds, with initially very high rates, similar to values reported for recently established reservoirs ($\sim$10 $\mu g/m^2$-yr), which declines over time to values reported for wetlands ($\sim$0.5 $\mu g/m^2$-yr). Even for older ponds which are at steady-state with respect to Hg_T inputs, these environments are net sources of $CH_3Hg^+_T$, which contrasts with freely draining upland catchments which exhibit net retention of $CH_3Hg^+_T$. The overall abundance of beaver ponds on the landscape is tied to changes in the population of beavers. Studies have shown that beaver populations in North America (and in Scandinavia), which declined to very low levels by 1900 as a result of over-exploitation (trapping), irrupted about 30 years after the re-introduction. In the boreal forest of northern Minnesota, a major episode of beaver pond construction occurred between 1940 and 1960, which still dominates the landscape today (Johnston & Naiman 1990). In Scandinavia, re-introduction started about 1920, with a major episode of pond building in the mid 1960's (Hartman 1994). It is likely that similar changes have occurred in the Adirondack region of New York, although quantitative information is lacking (Hammerson 1994). Increases in wetland area through the 1900's may have enhanced the transport of $CH_3Hg^+_T$ to downstream lakes and contributed to elevated concentrations of Hg observed for fish in the Adirondack region (Driscoll et al. 1995).

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References

Bishop K, Lee Y-H, Pettersson C & Allard B (1995) Terrestrial sources of methylmercury in surface waters: The importance of the riparian zone on the Svarterget catchment. Water Air Soil Poll. 80: 435–444

Bloom NS (1989) Determination of picogram levels of methylmercury by aqueous phase ethylation, followed by cryogenic gas chromatography with cold vapour atomic fluorescence detection. Can. J. Fish. Aquat. Sci. 46: 1131–1140

Branfireun BA, Heyes A & Roulet NT (1996) The hydrology and methylmercury dynamics of a Precambrian Shield headwater peatland. Water Resour. Res. (in press)

Burke J, Hoyer M, Keeler G & Scherbatskoy R (1995) West deposition of mercury and ambient mercury concentrations at a site in the Lake Chaplain Basin. Water Air Soil Poll. 80: 353–362

Cirmo CP & Driscoll CT (1993) Beaver pond biogeochemistry: acid neutralizing capacity generation in a headwater wetland. Wetlands 13: 277–292

Cirmo CP & Driscoll CT (1996) The impacts of a watershed $CaCO_3$ treatment of stream and wetland biogeochemistry in the Adirondack Mountains. Biogeochemistry 32: 265–297

Driscoll CT & van Dreason R (1993) Seasonal and temporal patterns in the chemistry of Adirondack lakes. Water Air Soil Poll. 67: 345–365

Driscoll CT, Wyskowski BJ, Cosentini CC & Smith ME (1987a) Processes regulating temporal and longitudinal variations in the chemistry of low-order woodland streams in the Adirondack Region of New York. Biogeochemistry 3: 225–241

Driscoll CT, Yatsko CP & Unangst FJ (1987b) Longitudinal and temporal trends in the water chemistry of the North Branch of the Moose River. Biogeochemistry 3: 37–62

Driscoll CT, Yan C, Schofield CL, Munson R & Holsapple J (1994) The mercury cycle and fish in the Adirondack lakes. Environ. Sci. Technol. 28: 136A–143A

Driscoll CT, Blette V, Yan C, Schofield CL, Munson R. & Holsapple J (1995) The role of dissolved organic carbon in the chemistry and bioavailability of mercury in remote Adirondack lakes. Water Air Soil Poll. 80: 499–508

Electric Power Research Institute (EPRI) (1994) Mercury Atmospheric Processes: A Synthesis Report. EPRI Report No. TR-104214

Engstrom DR, Swain EB, Henning TA, Brigham ME & Brezonik PL (1994) Atmospheric mercury deposition to lakes and watersheds. In: Baker LA (Ed) Environmental Chemistry of Lakes and Reservoirs. ACS Advances in Chemistry Series No. 237 (pp 33–66). American Chemical Society, Washington, DC

Fitzgerald WF, Mason RP & Vandal GM (1991) Atmospheric cycling and air-water exchange of mercury over mid-continental lacustrine regions. Water Air Soil Poll. 56: 745–768

Gilmour CC, Henry EA & Mitchell R (1992) Sulfate stimulation of mercury methylation in freshwater sediments. Environ. Sci. Technol. 26: 2281–2287

Hammerson GA (1994) Beaver (Castor canadensis): Ecosystem alteration, management and monitoring. Natual Areas J. 14: 44–xx

Hartman G (1994) Long-term population development of a reintroduced beaver (Castor fiber) population in Sweden. Conserv. Biol. 8: 713–717

Hecky RE, Ramsay DJ, Bodaly RA & Strange NE (1991) In: Suzuki T et al. (Eds) Advances in Hg Toxicology. Plenum Press, New York

Hudson RJM, Gherini SA, Fitzgerald WF & Porcella DB (1995) Anthropogenic influences on the global mercury cycle: a model-based analysis. Water Air Soil Poll. 80: 265–272

Johnston CA & Naiman RJ (1990) Aquatic patch creation in relation to beaver population trends. Ecology 71: 1617–1621

Johansson K, Aatrup M, Anderson A, Brinkman L & Iverfeldt A (1991) Mercury in Swedish forest soils and waters – assessment of critical load. Water Air Soil Poll. 56: 276–281

Krabbenhoft DP, Benoit JM, Babiarz CL, Hurley JP & Andren AW (1995) Mercury cycling in the Allequash Creek Watershed, Northern Wisconsin. Water Air Soil Poll. 80: 425–433

Lee U-H & Hultberg H (1990) Methylmercury in some Swedish surface waters. Environ. Toxicol. Chem. 9: 833–841

Lee Y-H & Iverfeldt A (1991) Occurrence and turnover of atmospheric mercury over the Nordic countries. Water Air Soil Poll. 25: 391–400

Lee Y-H, Borg GC, Iverfeldt A & Hultberg H (1994) Fluxes and turnover of methylmercury pools in forest soils. In: Watras CJ & Huckabee JW (Eds) Mercury Pollution Integration: and Synthesis (pp 329–342) Lewis Publishers, Boca Raton, Florida

Lee Y-H, Bishop K, Pettersson C, Iverfeldt A and Allard B (1995) Subcatchment output of mercury and methylmercury at Svartberget in northern Sweden. Water Air Soil Poll. 80: 455–465

Mason RP, Fitzgerald WF & Morel FMM (1994) The biogeochemical cycling of elemental mercury: anthropogenic influences. Geochim. Cosmochim. Acta 58: 3191–3198

Mierle G & Ingram R (1991) The role of humic substances in the mobilization of mercury from watersheds. Water Air Soil Poll. 56: 349–357

Rudd JWM (1995) Sources of methyl mercury to freshwater ecosystems: a review. Water Air Soil Poll. 80: 697–713

St. Louis VL, Rudd JWM, Kelly CA, Beaty KG, Bloom NS & Flett RJ (1994) Importance of wetlands as sources of methylmercury to boreal forest ecosystems. Can. J. Fish. Aquat. Sci. 51: 1065–1076.

St. Louis VL, Rudd JWM, Kelly CA & LA Barrie (1995) Wet deposition of methylmercury in northwestern Ontario compared to other geographic locations. Water Air Soil Poll. 80: 405–414

Zillioux EJ, Porcella DB & Benoit JM (1993) Mercury cycling and effects in freshwater wetland ecosystems. Environ. Tox. Chem. 12: 2245–2264