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Influence of Fluctuating Water Levels on Mercury Concentrations in Adult Walleye

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Atmospheric deposition of mercury (Hg) has been shown to be a significant source of Hg on the landscape (Rada et al. 1989; Swain et al. 1992) and is believed to contribute to increased Hg concentrations in aquatic food webs (Sorensen et al. 1994; Edwards et al. 1999). Methylmercury (MeHg) is the organic, bioavailable form of Hg that accumulates to toxic levels in top-level predators in aquatic systems (Suedel et al. 1994). Although limnological conditions in lakes and rivers can affect Hg methylation and concentrations in fishes, these relationships often vary among water bodies and fish species (McMurtry et al. 1989; Bodaly et al. 1993). Thus, regional studies are needed to identify mechanisms of local MeHg production and factors associated with Hg contamination in fishes.

The Prairie Pothole Region of North America has a unique variety of natural wetlands and glacial lakes that are important for fish, shorebirds, waterfowl, and humans. Cyclical climate, characterized by extended wet–dry periods, cause high variation in water surface area within the region (Rosenberry 2003). For example, consecutive years of high precipitation during the mid-1990s caused dramatic surface area increases in many glacial lakes and wetlands of eastern South Dakota. After lake levels increased, several fish populations were found to contain elevated Hg concentrations (>1 μg/g), prompting local officials to post fish consumption advisories (South Dakota Game, Fish and Parks, 2006).

The discovery of elevated Hg concentrations in fishes was surprising because (1) there were no apparent point-source inputs of Hg, and (2) the limnological conditions of most of these lakes (eutrophic, high pH) generally do not favor Hg methylation or bioaccumulation (Grieb et al. 1990; Pickhardt et al. 2002). Moreover, lakes that experienced large increases in surface area generally contained fast growing fish populations, a situation that usually lowers Hg concentration due to growth dilution (Rodgers and Qadri 1982; MacCrimmon et al. 1983). In this study, we document changes in lake surface area for glacial lakes in the Prairie Pothole Region and relate this to Hg concentration in adult walleye (*Sander vitreus*). Although a similar phenomenon is known to occur in reservoirs with fluctuating water levels (Jackson 1988; Snodgrass et al. 2000; Sorensen et al. 2005), widespread effects of surface area changes on Hg concentrations in fishes have not been documented in natural, glacial lakes. We hypothesized that increases in lake surface area enhanced

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Hg methylation and resulted in elevated fish Hg concentrations.

Materials and Methods

We studied 18 lakes within the Northern Glaciated Plains Ecoregion of eastern South Dakota (Fig. 1). Lakes in this region range from eutrophic to hypereutrophic and generally do not thermally stratify during summer months (i.e., polymictic mixing cycles). Changes in lake surface area were determined using Landsat 5 imagery (http://www.sdview.sdstate.edu) collected during the late 1980s (dry period) and early 2000s (wet period). Lake surface areas, determined from images obtained in 1987 and 2000, were digitized in ArcMap 9.1 to quantify the surface area (ha) of each lake for both time periods. We used regression analysis to assess the relationship between Hg concentrations in walleyes and percent change in surface area (SA) of lakes between wet (2000) and dry (1987) years.

Adult walleyes (350–500 mm total length TL) were collected during summer months (June through August) from 1996 to 2005 using a combination of electrofishing, trap-nets, and experimental gill-nets. Muscle samples (~2 g) obtained from 1996 to 2004 were collected from whole walleye fillets. A composite sample was obtained from five similar sized walleyes (50 mm size categories) then homogenized and analyzed for total Hg. Three to six composite samples were obtained from each lake and averaged to quantify walleye Hg concentration. In 2005, eight additional lakes were sampled and walleye fillets

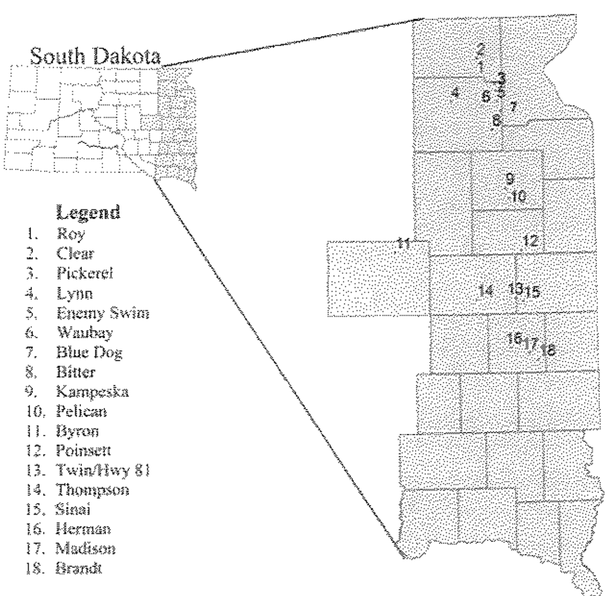

Fig. 1 Location of 18 study lakes in eastern South Dakota

(10–15 fish/lake) were analyzed individually for total Hg concentration, and then averaged to determine mean Hg concentration for the lake. All tissue samples were analyzed for total Hg using cold vapor atomic fluorescence spectrometry (Jones et al. 1997; Collin-Hansen et al. 2005; Yu 2005). The standard reference material (SRM) used was National Institute of Standards and Technology (NIST) #2976 muscle tissue. Our SRM contained 54.6 (2.1) ng/g total Hg. Fish samples were spiked at a level of either 0.5, 1.0, or 3.0 ng/g, with a detection limit of 0.02 ng/g. Percent spike recovery in our samples averaged 100.2 (4.6). Minimum detection limits for our fish tissue samples were <0.02 μg/g total Hg.

Information on watershed characteristics and water quality attributes were available for 10 of the 18 lakes we sampled (Stukel 2003). We used these data to explore relationships between walleye Hg concentrations and environmental factors. Variables were tested for homogeneity of variance and normality. Pearson correlations were used to identify significant relationships between individual parameters and walleye Hg levels ($\alpha = 0.05$)

Results and Discussion

Mean Hg concentrations in walleyes varied considerably among lakes, ranging from 0.05 (Pelican lake) to 0.99 μg/g (Bitter and Twin lakes; Table 1). Changes in lake surface area, as determined by difference (i.e., wet year–dry year), ranged from –54 ha (Lake Madison) to +3,683 ha (Waubay Lake). On a percentage basis, Lake Madison had the largest decrease in surface area (4.8%), while Lynn Lake expanded in size by over 300% (Table 1). Percent data were log transformed to correct for normality because we had a right-skewed distribution. The increase in lake SA associated with wet periods of the mid-1990s was significantly related to walleye Hg concentrations (n = 18, model $F_{[1,17]} = 26.0$, $r^2 = 0.62$, $p < 0.0001$; Fig. 2). Analysis of watershed and water quality variables from the ten lakes data set showed that most variables were poorly correlated to walleye Hg concentration, except SA change (Table 2).

Rapid increases in lake levels during the 1990s may be analogous to the "reservoir effect" and explain variation in Hg concentrations among the lakes we studied. Methylation of Hg in newly flooded soils may remain high for 10–15 years post-inundation (Porvari 1998; Bowles et al. 2003), so it is possible that walleye Hg concentrations will remain high for several more years. It appears that atmospheric Hg deposition in eastern South Dakota (Gossman 2003; EPA 2005) is not a trivial contribution and can accumulate in adjacent terrestrial soils and contribute to Hg contamination in aquatic food webs when flooding occurs. In our study, the magnitude of lake surface area expansions

Table 1 Surface area of lakes in 1987 (dry period) and 2000 (wet period), and mean Hg levels in adult walleyes collected from 1996–2005

Lake	Surface area 1987 (ha)	Surface area 2000 (ha)	Percent change in surface area	Walleye Hg (μg/g)	Sample collection year
Bitter	1309.9	4405.4	236.3	0.99	2005
Blue Dog	669.9	761.8	13.7	0.21	2000
Brandt	426.6	506.7	18.8	0.18	1998
Byron	751.8	746.9	–0.6	0.19	2005
Clear	468.7	484.7	3.4	0.14	1999
Enemy Swim	884.0	884.0	0.0	0.19	2005
Herman	521.3	502.2	–3.7	0.10	1996
Kampeska	1990.4	2046.8	2.8	0.30	2005
Lynn	157.2	643.4	309.4	0.57	2005
Madison	1109.3	1055.8	–4.8	0.21	1999
Pelican	1124.8	1124.8	0.0	0.05	2005
Pickerel	407.6	407.6	0.0	0.17	2000
Poinsett	3160.9	3160.9	0.0	0.13	1997
Roy	631.4	845.3	33.9	0.11	2005
Sinai	284.2	751.9	164.6	0.43	1996
Thompson	4989.9	5393.4	8.1	0.42	1996
Twin	364.9	1025.9	181.2	0.99	2005
Waubay	3648.2	7331.2	100.9	0.40	2001

The surface area of each lake was determined using Landsat 5 images collected in 1987 and 2000

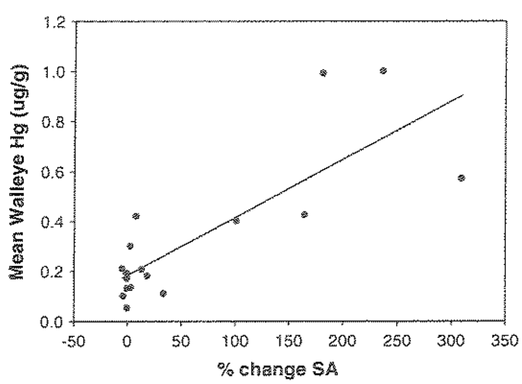

Fig. 2 Relationship between mean walleye Hg concentrations (μg/g) for eastern South Dakota glacial lakes and percent change in surface area (SA) between wet (2000) and dry (1987) years [$n = 18$, $F_{[1,17]}=26.0$, $p < 0.0001$, $r^2 = 0.62$, $y = 0.5296 + 0.372$(log percent change in surface area)]

was positively related to Hg concentrations in walleye (Table 1). However, it not known how the duration and/or frequency of wet–dry cycles affect Hg levels in specific water-bodies, because limnological conditions and water cycles vary between lakes.

Increased Hg concentrations measured in fishes following water level fluctuations could be associated with the frequency of inundation (Sorensen et al. 2005). Increased sulfate levels, caused by the drying and rewetting of soils, enhance sulfate reducing bacteria that produce MeHg. Lakes that endure recurrent annual wet–dry cycles likely experience lower sulfate mobilization than a lake that has not been inundated for many years (Gilmour et al. 2004; Sorensen et al. 2005). Thus, extended wet–dry periods in eastern South Dakota may have resulted in elevated sulfate concentrations that enhance Hg production and availability in these systems (St. Louis et al. 2004).

Productivity of glacial lakes may contribute to Hg concentrations in fish. For example, high walleye growth rates (based on age-3 TL) are typical in many lakes with elevated Hg concentrations (South Dakota Game, Fish and Parks 2006). Fast growing fish populations should result in fish with lower Hg concentrations owing to growth dilution (Norstrom et al. 1976; Olsson 1976; Verta 1990) and high algal productivity (Pickhardt et al. 2002; Essington and Houser 2003); however, based on growth data for age-3 walleyes reported in Stukel (2003), we found that walleye growth was positively correlated with mean Hg concentration (n = 10, $r = 0.695$, $p = 0.026$). The surface area changes that appear to enhance Hg methylation also increase the productivity of these systems. As a result, the buffering effect of high fish growth rates and primary productivity (decreased Hg burden per algal cell) may not be realized in natural lakes that increase in surface area because of the link between productivity and Hg accumulation.

Although variables such as pH, alkalinity, surface area, and watershed area explained fish Hg concentrations in

Table 2 Results from Pearson correlation analysis comparing mean walleye Hg concentrations with environmental variables from ten glacial lakes in eastern South Dakota

Parameter	*r*	*p*
WsL	–0.450	0.192
Vol:area ratio	0.397	0.257
Chl-*a* (mg/L)	0.391	0.263
pH	–0.006	0.987
Alkalinity (mg/L)	0.450	0.192
Conductivity (mS/cm)	0.252	0.483
% SA	0.759*	0.011*

pH, alkalinity, conductivity, and percent change in surface area between wet (2000) and dry (1987) years (% SA). Environmental data are from Stukel (2003)

WsL watershed area to lake surface area ratio, *Vol:area ratio* lake volume to surface area ratio, *Chl-a* chlorophyll-*a* concentration

*Significant correlations ($p < 0.05$)

other studies (McMurtry et al. 1989; Bodaly et al. 1993; Rudd 1995), they did not correlate with walleye Hg levels in our study (Table 2). This may be due to the high methylation rates resulting from organic matter decomposition that followed water level increases in the 1990s. Further, low pH (<7.0) increases microbial methylation of mercury (Wren and MacCrimmon 1983; Grieb et al. 1990; Hakanson 2003), but water pH was relatively high in our study lakes (mean = 8.9 ± 0.04 SE), and may explain why pH did not influence Hg contamination.

Our study lakes were located in close proximity to each other in eastern South Dakota (Fig. 1). Although the region experienced relatively uniform precipitation during the extended wet period of the mid-1990s, some lakes expanded faster and several years earlier than others. Lakes from early water-level expansions may be receding in MeHg production, and reduced MeHg production within a lake should result in lower total Hg concentrations in the resident fish communities. Moreover, many lakes experienced little to no change in surface area between wet and dry years (Table 1). Several of these lakes (i.e., Kampeska, Pelican, and Poinsett) have water control structures that maintain stable water levels in the lake, and generally contain fish with low Hg concentrations.

Recent fish consumption advisories in South Dakota (South Dakota Game, Fish and Parks 2006) indicate that Hg contamination is a concern. Walleye are a popular sport fish in the Prairie Pothole Region and their position as a primary piscivore makes them suitable for Hg monitoring (Wren and MacCrimmon 1986). More importantly, our results suggest that Hg contamination of walleyes and other sport fishes in Prairie Pothole lakes should be monitored regularly, particularly after lake levels increase. Lake surface area change may prove to be a reliable predictor of Hg concentrations, which would be useful for identifying lakes with a potential risk of Hg contamination.

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