A Literature-Based Assessment of Mercury and Methylmercury in Lake Ozette, Washington: Sources and Mediating Factors

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SUMMARY

There has been a global increase in methylmercury (MeHg) residues in fish in boreal (northern) climates. Atmospheric deposition of inorganic mercury (Hg) from volcanoes and coal-fired power plants is notable among other sources. The result has been consequential. Older, fish-eating (piscivorous) fish in many lakes throughout North America have bioaccumulated enough MeHg in their tissues to pose a risk to human health, particularly to the fetuses of pregnant mothers who frequently consume large quantities of these older fish.

Some of the fish species sampled from Lake Ozette in far northwestern Washington—notably two predators, largemouth bass and northern pike minnow—have elevated MeHg relative to fish sampled from other lakes in Washington. Logging in the watersheds draining into Lake Ozette has been postulated as one reason for the elevated MeHg residues measured in these fish.

Inorganic mercury has been deposited from the atmosphere into soils since the beginning of the industrial age and soil concentrations have accumulated with industrialization. Current point sources of atmospheric mercury include emissions from coal-fired power plants, cement plants and incinerators. Runoff from these soils—driven by rainfall—exports the Hg (either dissolved in water or bound to particulate matter) to water bodies. Wetlands are a notable sink for Hg inputs; they are depositional environments that often possess the anoxic conditions favoring methylation of Hg to MeHg. The MeHg can leach and otherwise be transported into streams and then lakes, where it is readily accumulated by phytoplankton, aquatic invertebrates, and then the invertebrates and fish comprising higher trophic levels in the food web. Because vertebrates cannot rid themselves of the mercury, it accumulates in their tissues throughout their lives. Fish live far longer than most invertebrates, so they accumulate greater residues of mercury.

There are many factors that affect transport of mercury from soils to wetlands, and there are many factors controlling transformation of inorganic mercury into MeHg and its transport into streams and lakes. These include rainfall, the amount and type of canopy cover, logging, fires, and the presence of wetlands. In water, wetlands, and sediment specific concentrations of pH, sulfate, dissolved organic carbon, particulate organic matter, and nutrients have been identified in multiple situations as being associated with Hg methylation. Logging and forest practices have been demonstrated to have a potential to increase the export of Hg and MeHg to waterbodies within watersheds. Current literature suggests that fires may have a lesser potential. The extent to which increased loadings translate into elevated residues in older fish depends particularly on the presence of wetlands, on dissolved organic carbon contents in surface waters, and on more acid pH levels. There are no clear, incontrovertible links between one activity, such as logging, and increased export of Hg or MeHg to surface waters downstream. The literature reports substantial variability in results and exceptions to cause-effect relationships. Therefore, the roles of logging, fire, wetlands, and water quality in producing elevated mercury bioaccumulation appear to be best understood with site-specific studies.

This paper examines the scientific literature concerning Hg contamination of fish and how it relates to site-specific conditions at Lake Ozette. We conclude that logging is only one potential mechanism responsible for Hg contamination of bass in Lake Ozette. However, it is apparent that there are multiple factors (e.g., extensive wetlands, historic channel clearing) that could be responsible, singly or more probably in combination, for mercury deposition in the lake and its consequent accumulation in the tissues of older, piscivorous fish.

INTRODUCTION

Statement of the Problem

Elevated levels of mercury, most of which is methylmercury (MeHg), have been measured in cutthroat trout, largemouth bass, northern pike minnow, and yellow perch collected from Lake Ozette, WA, between 2004 and the present (Seiders et al. 2007; Furl and Meredith 2008; Furl et al. 2010). Mercury residues in some of the fish sampled have been among the highest measured in Washington Department of Ecology's monitoring program (Furl and Meredith 2008; Furl et al. 2010). Measurement of total mercury (Hg) in sediment cores collected from Lake Ozette indicate that concentrations increased over time, peaking in the mid-1990s (Furl 2007). Logging in the Lake Ozette watershed has been postulated as one cause of the elevated bioaccumulation of mercury in some of the lake's larger fish (Furl et al. 2009). The purpose of this paper is to summarize information about the sources and transport of mercury to aquatic ecosystems/fish and to examine how these factors may influence delivery of methylmercury to the fish in Lake Ozette.

Approach

Computer searches were made of the literature databases Google Scholar, Google, Aquatic Sciences and Fisheries Abstracts, Aquatic Pollution, and Environmental Quality (CSA ProQuest), focusing on recent literature (1995-2010). Keywords were varied in the searches and included Lake Ozette, mercury, methyl mercury, methylmercury, sources, logging, fire, and forest practices. References were compiled into EndNote, and the EndNote file is available from the authors.

MERCURY IN AQUATIC ECOSYSTEMS

Definition of Terms

Inorganic mercury and total mercury are designated as Hg in this report. In the atmosphere, inorganic mercury occurs mainly as the elemental form Hg_o, but in fog and clouds it can be oxidized to Hg^{2+}, the form deposited in rainfall (Morel et al. 1998, Fig. 1). Under certain conditions in anoxic soils and sediments, anaerobic sulfur-reducing bacteria can methylate Hg to generate MeHg (Morel et al. 1998), which is primarily monomethylmercury (CH_3Hg) (Bloom 1992). Most (>95%) of the mercury measured in fish is CH_3Hg, usually reported as MeHg (Bloom 1992).

Fish bioaccumulate a majority of mercury from their food (Reinfelder et al. 1998; Chen et al. 2005; McIntyre and Beauchamp 2007). Because mercury cannot be detoxified and is excreted very slowly, fish cannot get rid of it and tissue residues increase with age (Reinfelder et al. 1998). Since age may be correlated with size, the highest Hg residues tend to occur in large, old, piscivorous fish (Tong et al. 1974; Fischnaller et al. 2003; McIntyre and Beauchamp 2007; Schwindt et al. 2008).

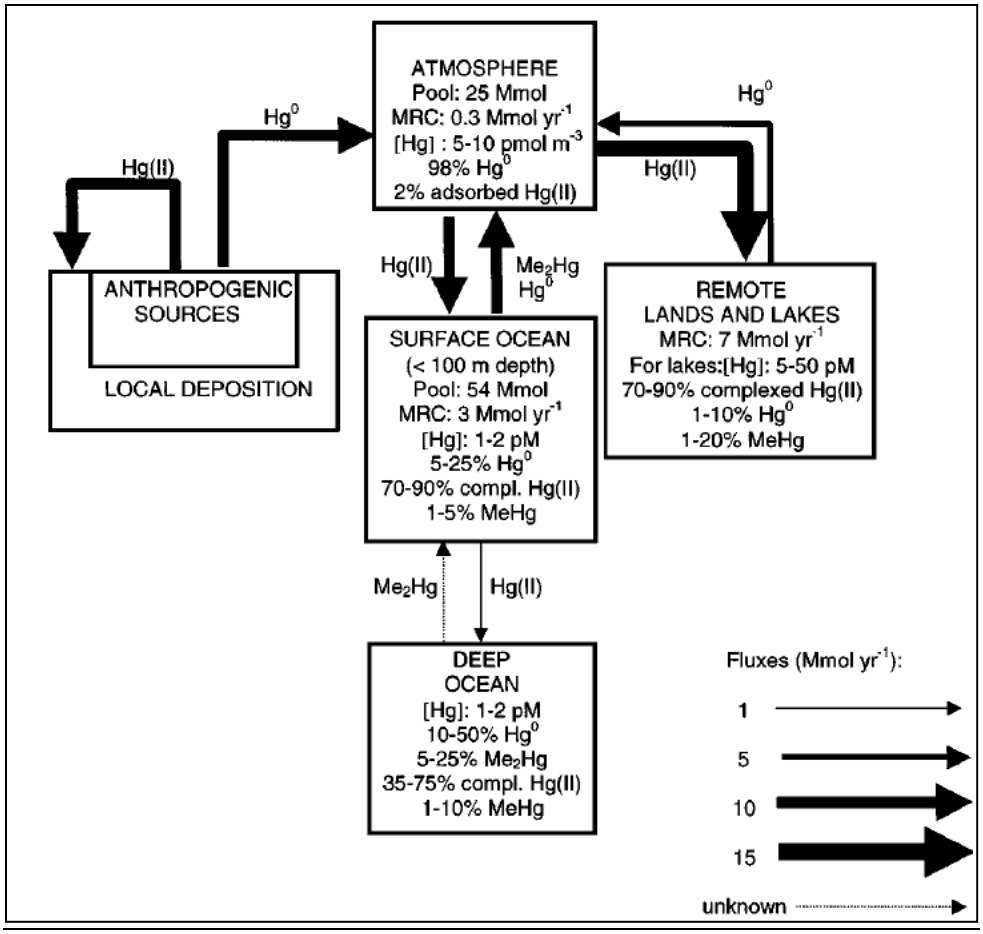

Figure 1. Global mercury cycle (Source: Fig. 1 in Morel et al. 1998).

Factors Influencing Methylmercury Generation

It has been known since 1957 (McAlpine and Araki 1959) that mercury can accumulate in aquatic food chains and reach high enough concentrations in the oldest specimens of some fish species to represent a health hazard to certain segments of the human population and to certain species of wildlife who frequently consume large quantities of contaminated fish. Societal concerns initially focused on controlling point sources of mercury contamination, originally chlor-alkali industrial plants and later coal-fired power plants, cement plants, and municipal incineration facilities (Driscoll et al. 2007). Over the last 20 years, the importance of mercury deposition from coal-fired power plants and natural sources such as volcanoes (Pyle and Mather 2003) has been recognized (Hanisch 1998; Seigneur et al. 2004; Hammerschmidt and Fitzgerald 2006). In the Lake Ozette area, most mercury presumably comes from globally-generated atmospheric deposition, as in most lakes far removed from point sources (Morel et al. 1998; Mason et al. 2005). There has been extensive study of the factors affecting the fate of mercury in aquatic environments due to its propensity to bioaccumulate in aquatic food chains, as will be evident below.

Atmospheric Sources

In the Pacific Northwest, precipitation-driven deposition of particulate, inorganic Hg in the atmosphere is the major source of Hg outside of urban areas and industrial sources such as electrical generating stations, and atmospheric Hg is the major source of mercury found in fish (Brumbaugh et al. 2001; Paulson 2004; Chen et al. 2005; Mason et al. 2005; Hammerschmidt and Fitzgerald 2006; Driscoll et al. 2007; Strode et al. 2008; Furl and Meredith 2010)[1]. In some cases the linkages between deposition, transport, and response (bioaccumulation in fish) are clear (Chen et al. 2005; Hammerschmidt and Fitzgerald 2006; Harris et al. 2007; Orihel et al. 2007), but they also can be obscure (Kolka et al. 1999). One reason is that accumulation has occurred over a long time, at least two centuries (Driscoll et al. 2007):

> *The response of fish methylmercury concentrations to changes in mercury deposition has been difficult to establish because sediments/soils contain large pools of historical contamination, and many factors in addition to deposition affect fish* (Harris et al. 2007)

Fate in the Terrestrial Environment

Inorganic mercury is deposited and then stored in the soils of the catchment (Kolka et al. 1999; Lee et al. 2000; Grigal 2002). Deposition rates depend on the areal extent of forest and the type of forest and on canopy cover, as the following study concluded:

> *Twice as much Hg and seven times as much DOC* [dissolved organic carbon] *was deposited in the forested watershed compared to the opening. Mass balance studies that are based on wet-only deposition in openings severely underestimate atmospheric deposition of Hg in forests. Conifer canopies are more efficient filters of airborne particulates than are deciduous canopies as indicated by much higher Hg concentrations and total deposition in throughfall and stemflow waters under conifers. Significant positive relationships existed between Hg and DOC in both throughfall (36–57% of the variation) and stemflow waters (55–88% of the variation). Hg complexation by DOC appears to be related to the contact time between precipitation and carbon sources* (Kolka et al. 1999).

Rainfall

The primary pathway for transferring mercury from the reservoir in soil to surface waters may be runoff to streams from rainfall (Caldwell et al. 2000; Grigal 2002; Watras et al. 2005; Regnell et al. 2009). Runoff provides MeHg to the base of the food chain, and the amount of MeHg in water, rather than in sediment, is the primary driver for the amount of mercury that accumulates in top predator fish (Brumbaugh et al. 2001; Mason et al. 2005, Chasar et al. 2009, Scudder et al. 2009).

Wetlands

Wetlands connected to streams and lakes via surface waters represent areas where dissolved and particulate-bound inorganic mercury in runoff is deposited and where methylmercury may be generated by anaerobic bacteria living in anoxic bottom sediments (Grigal 2002; Galloway and Branfireun 2003;

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[1] One study suggested that the sea may be a sink for mercury rather than a source to the land (as sea spray and mist) [Malcolm, E. G. and G.J. Keeler. 2003. The effects of the coastal environment on the atmospheric mercury cycle. J. Geophysical Res. 108(D12): ACH 4-1 to ACH 4-10.]

Watras et al. 2005; Stoor et al. 2006; Selvendiran et al. 2008; Verta et al. 2010). For example, Selvendiran et al. (2008) documented an increase in the percentage of MeHg (6%) at the outlet of a wetland associated with a forest compared to that at the inlet (2%). Loading of MeHg from the wetland also increased during the summer (0.27 ng/L) compared to the non-growing season (0.1 ng/L).

There is a close relationship between methylmercury in fish and the presence of wetlands, especially where the wetlands are connected to streams and lakes (Grigal 2002). In a large nationwide study of 291 streams, Scudder et al. (2009) reported that some of the highest levels of mercury in fish were found in tea-colored or "blackwater" streams in relatively undeveloped watersheds with abundant wetlands. In addition, they reported that streams with a high density of wetlands and forests and high concentrations of DOC in water were associated with high methylmercury concentrations. Grigal (2002) concluded that the most important terrestrial watershed property affecting MeHg flux is the proportion of wetland in the watershed, affecting both production of MeHg and water residence time, as illustrated in Figure 2.

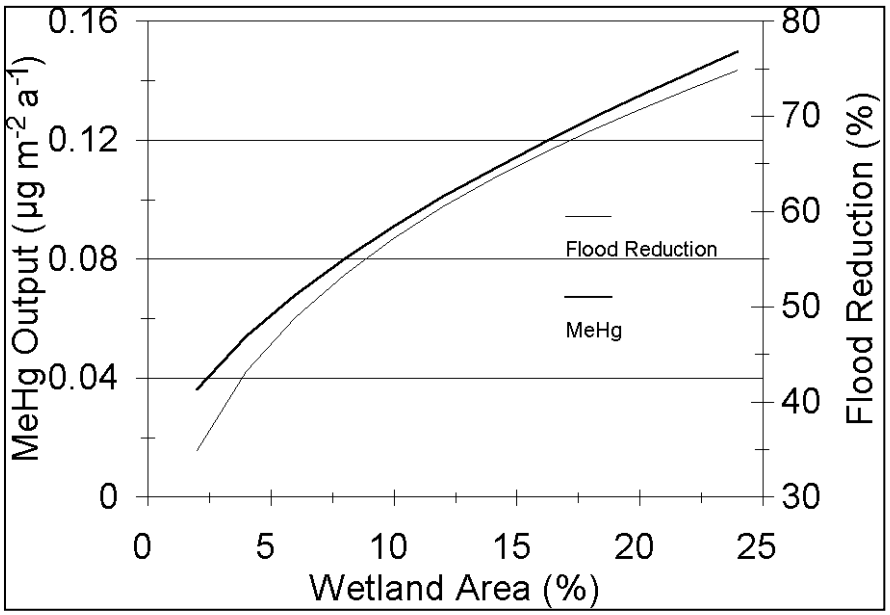

Figure 2. Relationship between the proportion of wetlands in a watershed and both the reduction in flood peak flow (stormflow) from watersheds in the midwestern U.S.A. and the mean annual MeHg flux. Source Figure 13 in Grigal (2002)

The wetland-MeHg relationship is complex, and many factors need to interact in ways that are variable and site-specific for significant MeHg generation to occur, including:

1) an upstream source of Hg,
2) deposition of Hg within the wetland or lake (Mailman et al. 2006),
3) wetland hydrology and connectivity with the waterbody (Galloway and Branfireun 2003),
4) anoxic sediment with sufficient electron donors (e.g., sulfate SO_4^{2-})(Garcia and Carignan 1999; Garcia and Carignan 2000; Chen et al. 2005),

5) Acidic pH, particularly in the water immediately overlying sediment and in the sediment interstitial or porewater (Garcia and Carignan 1999; Garcia and Carignan 2000; Brumbaugh et al. 2001; Chen et al. 2005),

6) elevated organic carbon in the water (Grigal 2002; Garcia and Carignan 2005; Selvendiran et al. 2008; Eriksson et al. 2010),

7) aging over time (pedogenesis[2]) of organic matter in terrestrial soil, the major source of Hg to waterbodies (Kolka et al. 1999; Ouellet et al. 2009),

8) nutrient (trophic status)(Allen et al. 2005).

Logging and Forest Practices

Logging has the potential to significantly increase loading of Hg and MeHg to waterbodies within a watershed (Garcia et al. 2007; Skyllberg et al. 2009) (Figure 3). The magnitude of increased loading varies: Bishop et al. (2009) estimated the increase at 10-25%; Eriksson et al. (2010) measured a threefold increase from 0.3 mg MeHg per hectare per year to 0.9 mg MeHg per hectare per year. Measurements by Skyllberg et al. (2009) were similar to those of Bishop:

> *Assuming that MeHg and HgII are mobilized from soil to stream to a similar relative extent as a consequence of clear-cutting, a calculation showed that 1/6 of the elevated MeHg concentration was due to enhanced mobilization from soil and 5/6 was due to new methylation of HgII 0-4 years after clear-cut. New methylation after clear-cut is suggested to be stimulated by an increased availability of electron donors for methylating bacteria, as a consequence of degradation of logging residue ("slash") and soil organic matter.* Source (Skyllberg et al. 2009).

Sørensen et al. (2009) reported a 15% increase in Hg concentration and 20-30% increases in the flux of Hg from soil to streams after logging. MeHg transport was not proportional to that of Hg; rather, it either declined or increased by up to 60%, the latter depending on whether annual MeHg peaks during summer low flows had been influenced by forest harvest. Porvari et al. (2003) found that changes in Hg concentrations in water after logging were variable (depended on year and season of comparison), but that increases in runoff after logging had major impacts on total Hg and MeHg output. They suggested that the reduction in evapotranspiration after logging not only increased runoff, but may have increased the areas of saturated soils and wetlands that could stimulate Hg methylation and contribute MeHg to adjacent streams.

Grigal (2002) reported that logging could have a variable affect on the production of MeHg as a result of variability in DOC export following logging. He cited studies where timber harvest increased DOC export and other studies where harvesting had little effect on DOC. Porvari et al. (2003) found that Hg was positively correlated with total organic carbon (TOC) concentrations in runoff, but not correlated with MeHg. Consequently, they postulated that TOC may explain much of the increase in total Hg concentration and outflow, but does not explain the increase in MeHg.

[2]Pedogenesis is the process by which soil is created (formed) over time.

All the logging effects studies indicate that increased Hg output is generally associated with disturbance of forest soils, alteration of water flow paths, and changed hydrology that mobilize Hg that is already present in the soil. None of the studies that we reviewed examined the role of forest roads *per se*, although some examined tractor tracks (Bishop et al. 2008).

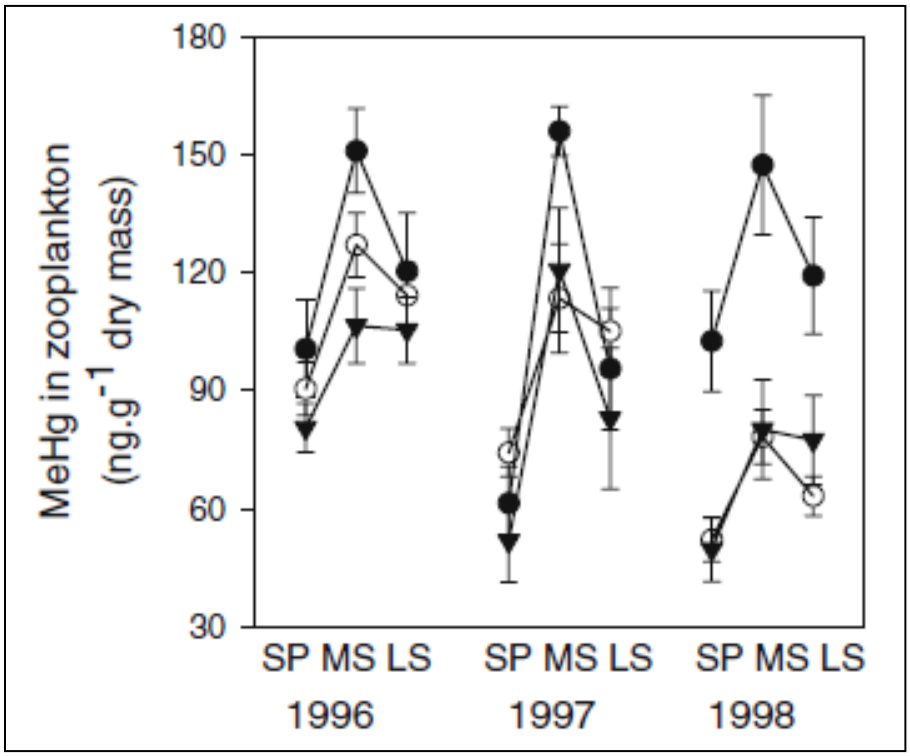

Figure 3. MeHg in zooplankton from lakes in catchments affected by logging (●) and fire (▼) compared to reference catchments (○). SP = spring; MS = midsummer and LS = late summer. Source: Figure 2 in Garcia et al. (2007).

Fire

Forest fires can also increase loadings of Hg and MeHg to waterbodies and bioaccumulation in fish (Kelly et al. 2006; Witt et al. 2009), but the consequences of fire also appear to be quite variable. For example, Kelly et al. (2007) found that forest fire followed by a rain storm caused a large short-term release of total Hg and MeHg to streams and lakes of the Moab Lake watershed, Alberta, CA (Figure 4). The Hg pulse was rapidly transferred up the food chain and resulted in greater concentrations of Hg in rainbow trout of lakes in partially burned catchments compared to those from reference catchments. Caldwell et al. (2000) monitored total and MeHg concentrations in sediments of Caballo Reservoir, NM after a July 1995 wildfire and found concentrations of MeHg at the Palomas site increased 30-fold by October 1995 and was an order of magnitude greater than concentrations at other more distance sites in the reservoir. The Palomas site was nearest the outlet of an intermittent creek draining the watershed where the fire occurred. They concluded that fire followed by a late summer storm mobilized mercury from the watershed and deposited mercury-bound organic matter into the reservoir which promoted microbial methylation and elevated MeHg levels. Less dramatic responses to fire have also been

observed. For example, two years after fire, Allen et al. (2005) found MeHg concentrations in four of five macroinvertebrate taxa and in brook stickleback did not differ between burned and reference drainage basins in the Swan Hills region of west-central Alberta. They suggest that the weak response may be due a combination of factors including the deep glacial soils in Boreal Plain catchments and the relatively low catchment area to lake volume ratios which reduce the potential for surface runoff and yielded volumes too small to affect lake water chemistry. Similarly, in a comparative study of burned and unburned areas of Voyageurs National Park, MN, Woodruff et al. (2009) found no significant changes in aqueous total mercury and total organic carbon concentrations in lake water and no changes in the concentration of MeHg in age-1 yellow perch following a fire in the Shoepack Lake watershed. They concluded that in watersheds with relatively subdued topography most of the mercury released by fire does not enter the lake or aquatic food web.

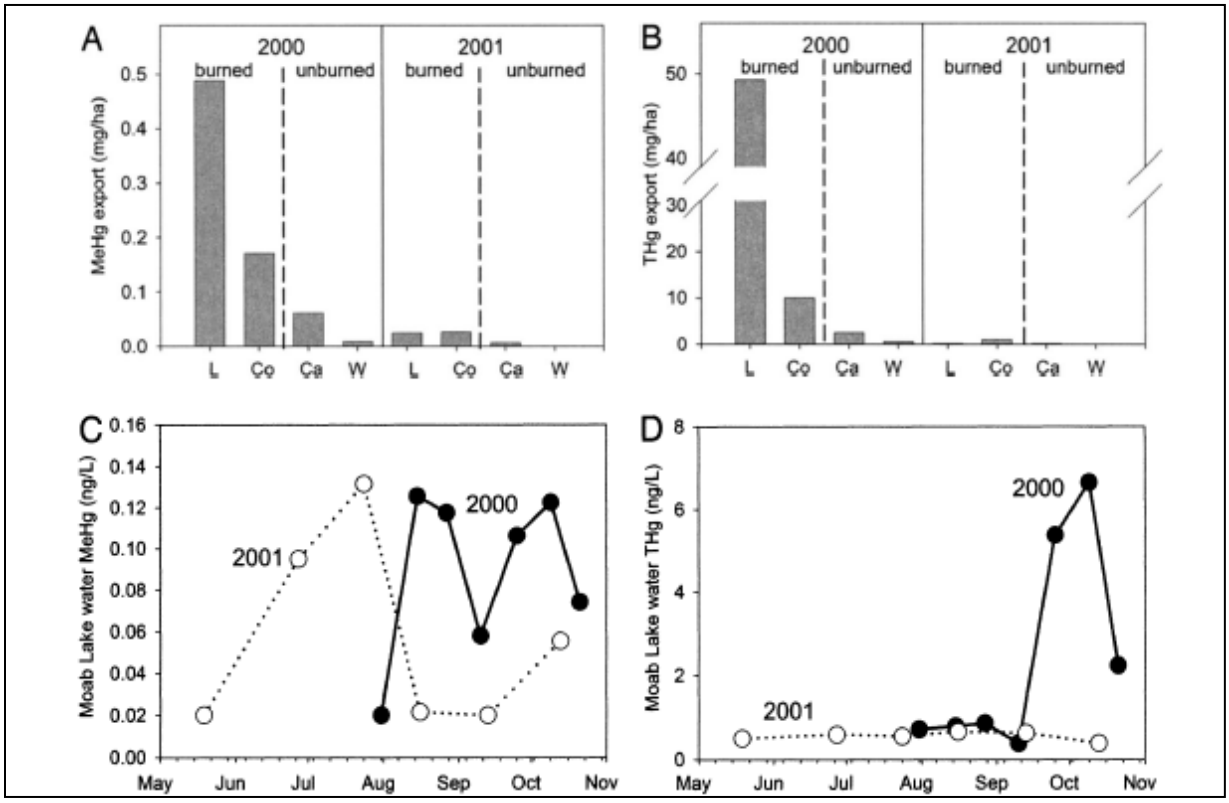

Figure 4. MeHg and total Hg (THg) export from burned and unburned catchments near Moab Lake, Alberta, and MeHg and THg concentrations in the Lake's surface waters. (A and B) Export of MeHg (A) and THg (B) from two burned catchments—Lake Creek (L; 29.3% burned) and Corral Creek (Co; 68.4% burned)—and two unburned catchments—Cavell Creek (Ca) and Wabasso Creek (W). (C and D) Seasonal concentrations of MeHg (C) and THg (D) in unfiltered water from Moab Lake in 2000 and 2001. Source: Figure 3 in Kelley et al. (2006).

MERCURY IN LAKE OZETTE

Lake Ozette Watershed and Land Use

Lake Ozette is a large (7,550 acres), deep (320 ft maximum depth), oligotrophic lake in northwestern Washington. The physical characteristics of the watershed are described by NOAA (2009):

> *The terrain of the Ozette watershed is slightly rolling to steep, with a gradual increase in elevation from zero feet at sea level (at the Ozette River mouth), to 34 feet at the lake's outlet, to just under 2,000 feet at the watershed's highest point in the upper Big River watershed. Most of the watershed ranges from 200 to 800 feet elevation. The geology of the Ozette watershed is an interesting mix of flat and gently sloping glacial and glacio-fluvial deposits situated between resistant knobs and small hills composed of Tertiary marine sedimentary rock units mechanically weak silt- and sand-stones). Some glacial landforms extend for several square miles, while others occupy small valleys. Other portions of the watershed (e.g., upper Big River) are steep and rugged and are underlain by Eocene-age volcanic flows and breccias. The climate of the northwest Olympic Peninsula can be characterized as temperate coastal-marine, with mild winters and cool summers. Annual precipitation at the Quillayute State Airport from 1967 to 2005 averaged 102.6 inches. The bulk of this precipitation fell as rain between October and April.*

Land ownership and land use are also described by NOAA (2009):

> *Private land includes large industrial forest landowners and small forest, residential, and agricultural landowners, and makes up approximately 62 percent of the basin. The NPS manages 25.8 percent of the basin, WDNR manages 8.4 percent, and the Makah Tribe (Ozette reservation) owns less than 1 percent. Private landowners own an average of 90 percent of the watersheds of the four largest tributaries to Lake Ozette and the Ozette River (Big River, Crooked Creek, Umbrella Creek, and Coal Creek). With the exception of Big River, zoning within these four sub-basins is 99 to 100 percent commercial forest.*
>
> *Along Big River, agricultural and residential development has been confined to the lower 10 miles of the river. Most residential development along Big River is near the original wagon trail. Currently, about 245 acres of land (~1.2 percent of the watershed area) are cleared for residential or agricultural use, and there are approximately 62 houses and other buildings within the Big River valley. In agricultural areas, the riparian zone and floodplain of the river were cleared of vegetation and converted to pasture. Currently, approximately 9,900 feet of Big River shoreline are adjacent to developed residential or agricultural land.*

In addition to forest harvest and land clearing for agriculture, the lake outlet (Ozette River) and many tributaries to the lake have been altered by channel clearing projects. Large wood was removed from the Ozette River and from the lower reaches of the larger tributaries during the 1950s (Haggerty et al. 2009). These projects caused a drop in lake level and destabilization of stream channels resulting in significant sediment delivery to the lake from bank erosion, channel incision, channel widening, and channel migration (Herrera 2006). Herrera (2006) reported that channel degradation was widely observed in the channel network of the Ozette watershed during a 2004 survey and that channel destabilization in Big River was largely due to the removal of log jams.

Forest Harvest and Mercury in Fish of Lake Ozette

It is clear that sedimentation rates in Lake Ozette have increased over the past 50 or more years. Sedimentation is probably a result of cumulative watershed disturbances from logging, agriculture, channel clearing, and land development activities (Herrera 2006; Haggerty et al. 2009). In addition, it is evident from the forgoing review that such watershed disturbances can mobilize Hg and increase the flux of Hg and MeHg to streams and lakes. However, the postulation by Furl et al. (2009) that logging is responsible for the high levels of mercury in largemouth bass in Lake Ozette is not supported by the available facts.

First, the assertion that increasing Hg flux is due to logging because sedimentation rates are coincident with logging appears to be unsupported by the historical record. Figure 4 shows that Hg flux varied little prior to 1988 (range ≈70 to 100 µg/m^2/yr), then increased rapidly from 100 to about 260 µg/m^2/yr by 2000. Yet most of the watershed was logged prior to 1988 (i.e., 74% of old growth had been clear-cut), and after 1988 only about 11% of the watershed was logged (Figure 5).

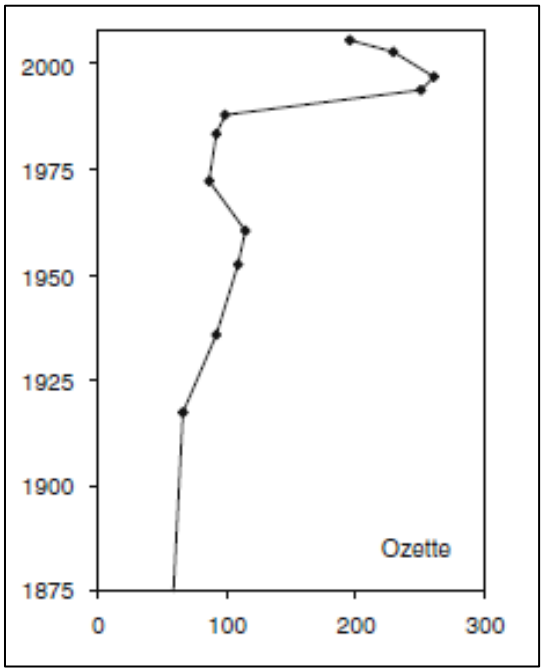

Figure 4. Estimated flux of mercury to Lake Ozette sediments. Source: Figure 4 of Furl et al. (2009). X-axis is Hg flux (µg/m^2/yr) and y-axis is the year in which Hg deposition to the sediment has been estimated to have occurred.

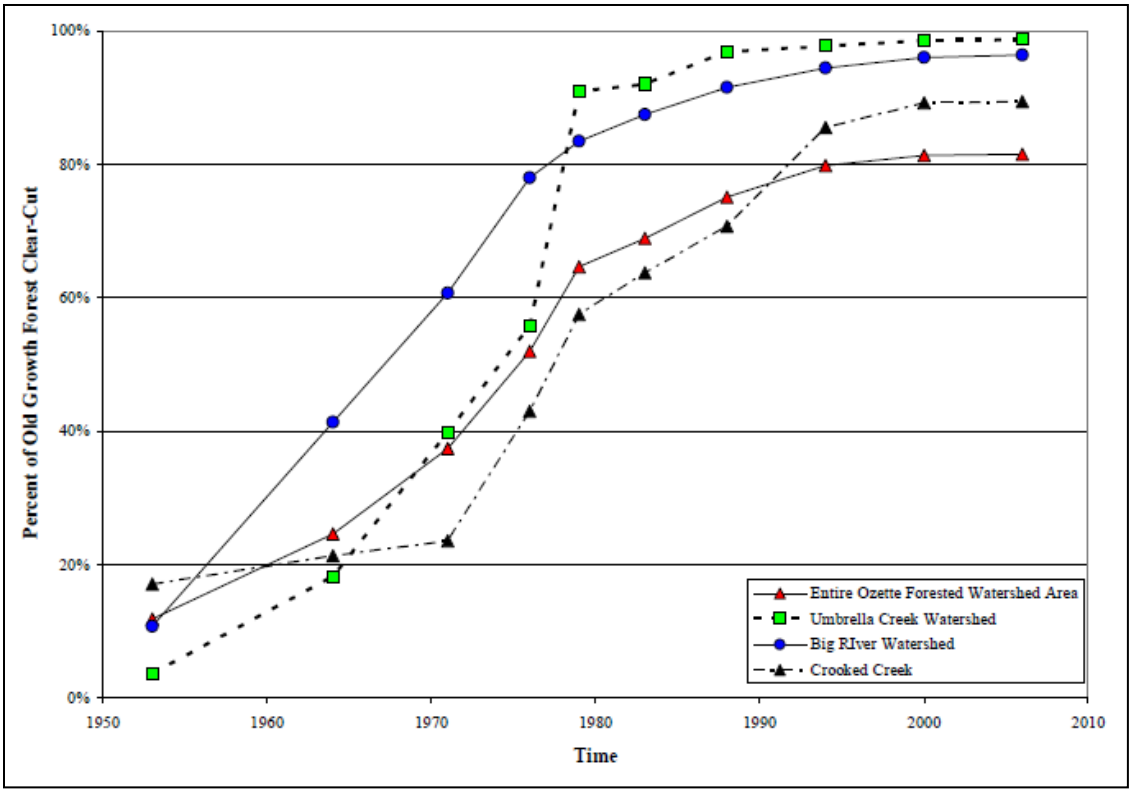

Figure 5. Percentage of old growth forest clear-cut over time in the Lake Ozette watershed. Source: Figure 1.11 in Haggerty et al. (2009).

If logging was responsible for the increased Hg flux, the greatest flux should have been associated with the period of intense logging and the response should have been rapid, as observed in other studies. Yet the data show just the opposite (i.e., greatest Hg flux corresponded to recent period of least logging). Similarly, the flux of Hg to Lake Ozette sediments, which Furl et al. (2009) estimated changed little prior to 1988, increased greatly after 1988, much later than the historical rate of logging (see Figure 5 above and Figure 6 in Furl et al. 2009). Either recent logging is producing more sediment than earlier logging, or other things happening in the watershed are contributing significantly to the overall sediment loading of Lake Ozette. The former is unlikely, because logging regulations intended to protect riparian areas and reduce sediment inputs from mass wasting and roads have continually improved since the 1980s. Rather, the legacy impacts of channel clearing and the absence of riparian protection on agricultural lands is probably responsible for a large proportion of sedimentation in recent decades (Haggerty et al. 2009). Herrera (2006) reported that past wood removal from the Ozette River and Big River initiated an evolving sequence of channel degradation and aggradation that continue to produce moderate to high levels of channel sedimentation in most of the major tributaries to the lake. Further, Megahan (2007) pointed out that past removal of wood in the lower tributaries continues to influence bank erosion of fine-grained alluvial soils (Tealwhit soils) and is probably the primary cause of high suspended sediment concentrations and associated turbidity in the area streams. The Tealwhit and similar soils (e.g., Ozette silt loam, Kydaka-Zeeka silty clay loam) in the Ozette watershed are highly erosive and typically contain hydric soils (NRCS 2010), the latter being significant to formation of MeHg.

The extensive wetlands and hydric soils in the Ozette watershed may also be potentially significant areas for storage of Hg and production of MeHg. The literature strongly implicates wetlands as a key source of MeHg, with strong positive correlations between MeHg accumulation in fish and the percentage of wetlands in a watershed (Snodgrass et al. 2000; Brumbaugh et al. 2001; Chen et al. 2005; Driscoll et al. 2007; Bishop et al. 2009; Ward et al. 2010). Furthermore, research indicates that increasing basin percentages of forests and wetlands proximal to streams are the best predictors of Hg in largemouth bass (Scudder et al. 2009). The Lake Ozette watershed is mostly forested with approximately 1,867 acres of wetlands (4.2% of watershed area not including forested wetlands and numerous small unmapped wetlands), and a large proportion of the wetlands occur adjacent to the lake and tributary streams (Figure 6). In addition, the low-gradient wetlands at the mouths of several lake tributaries enable direct access by top level predators (i.e., largemouth bass) to feeding areas with potentially high levels of Hg. Furl et al. (2009) acknowledged the potential effect of wetlands on MeHg production, but did not address their influence on Hg contamination of fish in Lake Ozette compared to levels measured in fish of others lakes in the study. The literature suggests that the presence of wetlands alone could account for the differences in Hg levels among the lakes studied by Furl et al. (2006). Consequently, it is important to account for wetlands in assessing the fate of Hg in Lake Ozette and its watershed.

Third, channel clearing activities during the 1950s need to be considered as increased sources of Hg and MeHg to Lake Ozette. The lowered lake level and tributary channel incision not only caused increased erosion and sedimentation, but probably caused significant drainage from the adjacent wetlands and poorly drained soils. Grigal (2002) cited studies where drainage of peatlands increased both MeHg and total Hg flux. One comparative study found an increase in sediment concentrations of Hg in a lake associated with drained peatlands, but no change in another lake where peatlands in the watershed were undisturbed. In Lake Ozette the increasing trend in sediment Hg concentrations during the 1950s, which peaked in about 1965 (see Figure 4; Furl et al. 2009), may have been a result of channel disturbances and wetland drainage. In comparison, at Dickey Lake, which also has wetlands and poorly drained soils similar to Lake Ozette (RTOC 1998), sediment Hg concentrations varied little over the same time period (see Figure 4; Furl et al. 2009). In Dickey Lake the logging history is similar to that of Lake Ozette, but there is no history of channel clearing and only minor land development during the 1890s that did not persist (RTOC 1998).

The forgoing demonstrates the complex factors influencing MeHg production, transport, and contamination of fish. The Furl et al. (2009) conclusion that logging is responsible for Hg contamination of bass in Lake Ozette only addresses one potential mechanism. It is apparent that there are multiple factors that could be responsible, singly or probably in combination, for mercury deposition in Lake Ozette and the consequent accumulation in the aquatic food chain, in particular in the tissues of older, piscivorous fish. Site-specific studies are required to identify and quantify the relative contributions of Hg from the various land uses.

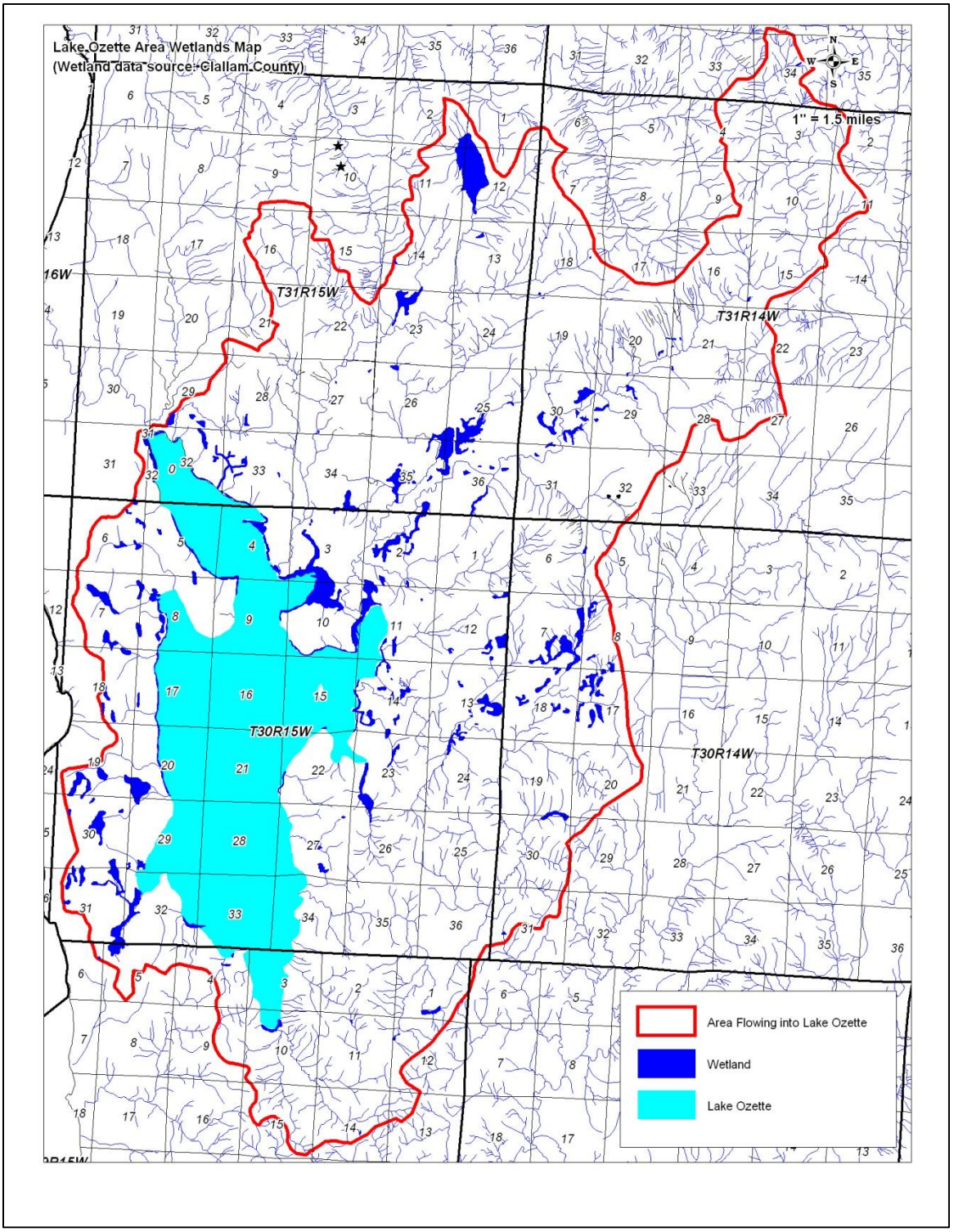

Figure 6. Map of Lake Ozette watershed showing location of wetlands. Wetlands Source: Clallam County; available: http://www.clallam.net/Map/

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