Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Reservoirs and water management influence fish mercury concentrations in the western United States and Canada

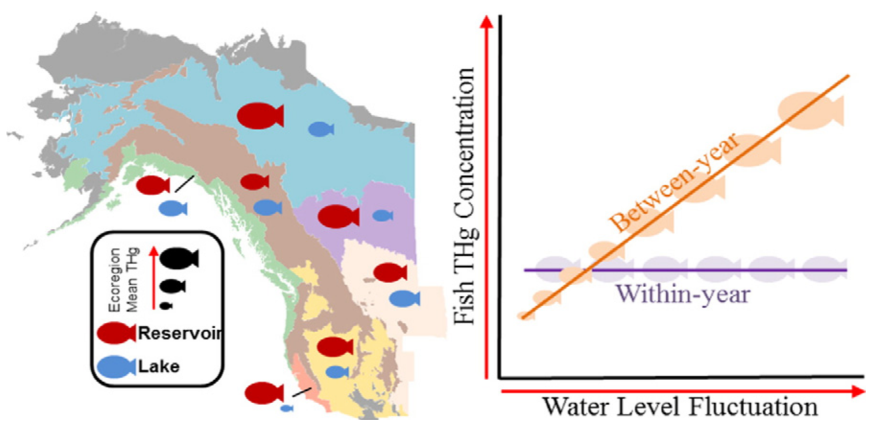
James J. Willacker [a,*], Collin A. Eagles-Smith [a], Michelle A. Lutz [b], Michael T. Tate [b], Jesse M. Lepak [c], Joshua T. Ackerman [d]

[a] U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, 3200 SW Jefferson Way, Corvallis, OR 97331, USA
[b] U.S. Geological Survey, Wisconsin Water Science Center, 8505 Research Way, Middleton, WI 53562, USA
[c] Colorado Parks and Wildlife, 317 West Prospect Rd., Fort Collins, CO 80526, USA
[d] U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, 800 Business Park Drive, Suite D, Dixon, CA 95620, USA

HIGHLIGHTS

- Fish Hg concentrations were compared in lakes and reservoirs of western N. America.
- Hg concentrations were higher in reservoirs than lakes in some ecoregions.
- Peak Hg concentrations occurred in 3 year old reservoirs and then declined.
- Timing of minimum storage and between-year fluctuation effected Hg concentrations.
- Water management practices influence Hg bioaccumulation in many reservoirs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 November 2015
Received in revised form 8 March 2016
Accepted 8 March 2016
Available online xxxx

Keywords:
Lakes
Methylmercury
Post-impoundment
Season
Water level fluctuation
Western North America Mercury Synthesis

ABSTRACT

Anthropogenic manipulation of aquatic habitats can profoundly alter mercury (Hg) cycling and bioaccumulation. The impoundment of fluvial systems is among the most common habitat manipulations and is known to increase fish Hg concentrations immediately following impoundment. However, it is not well understood how Hg concentrations differ between reservoirs and lakes at large spatial and temporal scales or how reservoir management influences fish Hg concentrations. This study evaluated total Hg (THg) concentrations in 64,386 fish from 883 reservoirs and 1387 lakes, across the western United States and Canada, to assess differences between reservoirs and lakes, as well as the influence of reservoir management on fish THg concentrations. Fish THg concentrations were 1.4-fold higher in reservoirs (0.13 ± 0.011 μg/g wet weight ± standard error) than lakes (0.09 ± 0.006), though this difference varied among ecoregions. Fish THg concentrations were 1.5- to 2.6-fold higher in reservoirs than lakes of the North American Deserts, Northern Forests, and Mediterranean California ecoregions, but did not differ between reservoirs and lakes in four other ecoregions. Fish THg concentrations peaked in three-year-old reservoirs then rapidly declined in 4–12 year old reservoirs. Water management was particularly important in influencing fish THg concentrations, which were up to 11-times higher in reservoirs with minimum water storage occurring in May, June, or July compared to reservoirs with minimum storage occurring in other months.

* Corresponding author.
E-mail address: jwillacker@usgs.gov (J.J. Willacker).

http://dx.doi.org/10.1016/j.scitotenv.2016.03.050
0048-9697/Published by Elsevier B.V.

Between-year changes in maximum water storage strongly influenced fish THg concentrations, but within-year fluctuations in water levels did not influence fish THg concentrations. Specifically, fish THg concentrations increased up to 3.2-fold over the range of between-year changes in maximum water storage in all ecoregions except Mediterranean California. These data highlight the role of reservoir creation and management in influencing fish THg concentrations and suggest that water management may provide an effective means of mitigating Hg bioaccumulation in some reservoirs.

Published by Elsevier B.V.

1. Introduction

Mercury (Hg) contamination is globally ubiquitous in aquatic ecosystems (Driscoll et al., 2013). Western North America presents a particularly heterogeneous landscape of diverse Hg sources from legacy mining and atmospheric deposition, coupled with extreme gradients in habitats and environmental conditions (Eagles-Smith et al., 2016b). The aridity gradient in western North America has fostered widespread human modification of aquatic environments, which influence Hg risk because of associated alterations to complex biogeochemical and ecological processes that regulate the production and bioaccumulation of methylmercury (MeHg), the most common and toxic form of Hg in biota (Clarkson and Magos, 2006). This is important because MeHg production can influence Hg concentrations in biota more than total inorganic Hg inputs in some systems (Benoit et al., 2003; Suchanek et al., 2008; Wiener et al., 1990). Reservoir creation, and associated hydrologic management, are among the most widespread anthropogenic modifications of aquatic ecosystems, and may influence Hg cycling and MeHg bioaccumulation at a global scale (Rosenberg et al., 2000).

The modern development of western North America was made possible by impounding waterways to create reservoirs for water storage, irrigation, flood control, and hydropower (Travis, 2003). There are nearly 23,000 dams in the western United States (Graf, 1999) that are capable of storing almost 6 times the mean annual runoff of the region (Sabo et al., 2012; Sabo et al., 2010). Although dams provide many social and economic benefits to society, impounding natural waters fundamentally alters the functioning of riverine ecosystems. Impoundment changes geomorphological processes, both in the inundated reach and downstream (Kingsford, 2000; Sabo et al., 2012); biogeochemical processes such as organic carbon transport, nutrient inputs, and oxygenation (Friedl and Wüest, 2002); and ecological processes such as community composition, ecosystem productivity, and bioenergetics (Bunn and Arthington, 2002; Ligon et al., 1995). Thus, the semi-fluvial nature of reservoirs coupled with their manipulated hydrologic cycles make reservoirs unique from most non-impounded lakes (Friedl and Wüest, 2002; Hall et al., 2005). All of these processes play fundamental roles in the distribution, methylation, and bioaccumulation of Hg (Hall et al., 2005), and thus may result in differences in Hg cycling between reservoirs and non-impounded lakes.

The influence of reservoir creation on mercury cycling, frequently referred to as the 'reservoir effect' (Bodaly et al., 1984; Jackson, 1988; Stewart et al., 2008), is a well-documented phenomenon (Bodaly et al., 1984; Hall et al., 2005; Hecky et al., 1991; Lodenius et al., 1983; St. Louis et al., 2004; Verta et al., 1986) resulting in elevated MeHg concentrations in biota following reservoir impoundment. These increases in biotic MeHg concentrations have largely been attributed to enhanced microbial methylation of inorganic Hg resulting from inundation of terrestrial organic matter and favorable redox conditions in flooded soils (Bodaly et al., 1984; Friedl and Wüest, 2002; Hall et al., 2005; Lucotte et al., 1999). Thus, factors that influence the quantity and quality of organic matter or the prevalence of anoxia result in substantial variation in the magnitude and duration of increases in MeHg concentrations after reservoir creation (Hall et al., 2005; Johnston et al., 1991; Larssen, 2010; Verta et al., 1986). Even after the initial pulse of MeHg production associated with reservoir creation, the structure and management of reservoirs continue to influence Hg cycling (Caldwell et al., 2000; Eckley et al., 2015; Hall et al., 2005). Despite the established influence of reservoir creation on fish MeHg concentrations, relatively little is known about how reservoir management influences fish Hg concentrations, nor how these contamination levels differ from more natural lake ecosystems across large landscapes.

The hydrologic cycles of reservoirs are highly managed and dependent on the purpose of each reservoir. As a result, many reservoirs experience substantial water level fluctuations, with widely different timing and duration (Grigg, 1996; Poff and Hart, 2002). For example, reservoirs managed for flood control are often maintained at low water levels, but experience large fluctuations during precipitation events, whereas reservoirs managed for other purposes may have more stable water levels (Eckley et al., 2015; Poff and Hart, 2002). This is important, because repeated wetting and drying of sediments associated with water level management may further stimulate methylation of inorganic Hg (Eckley et al., 2015; Snodgrass et al., 2000). However, the magnitude of this effect is likely dependent upon the extent, timing, and duration of water level fluctuations. Three sediment regions are associated with water level fluctuations; 1) permanently inundated sediments, 2) sediments exposed to the atmosphere for relatively short (≤1 year) periods, and 3) sediments exposed for longer (>1 year) periods, but still periodically inundated. Exposure of sediments for longer periods may be especially important for MeHg production due to associated increases in sediment re-oxidation and colonization by early successional vegetation, which stimulate MeHg production upon re-inundation (Larson et al., 2014; Selch et al., 2007; Snodgrass et al., 2000; Sorensen et al., 2005). Further, identifying the effects of between- versus within-year water level fluctuations on fish THg concentrations may be particularly valuable in understanding, and adaptively managing, the impacts of extended droughts, which have become increasingly common in western North America.

Broad, landscape-scale studies that compare Hg concentrations in fish from reservoirs to those from non-impounded lakes are limited due to the difficulty of comparing impoundments in differing stages of development to natural lakes (Depew et al., 2013a; Depew et al., 2013b; but see Kamman et al., 2005; and Monson et al., 2011). Further, it is unclear how contemporary water management influences Hg concentrations in reservoirs. Thus, an extensive dataset of Hg concentrations in fish from reservoirs and non-impounded lakes across the western United States and Canada was compiled to test whether Hg concentrations in fish differed between reservoirs and non-impounded lakes across this broad geographical area. Additionally, the influence of reservoir age and water management practices on fish Hg concentrations was assessed.

2. Materials and methods

2.1. Mercury data compilation

Fish total mercury (THg) concentration data from reservoirs and lakes were compiled from a variety of existing sources including: monitoring programs, non-routine surveys, and government and academic research projects occurring in the western United States and Canada (Eagles-Smith et al., 2016a; Fig. S1). The resulting dataset included data collected with a variety of analytical methods during a period of over four decades (1969–2011). Although analytical technology has