

Focus articles are part of a regular series intended to sharpen understanding of current and emerging topics of interest to the scientific community.

An Environmental Problem Hidden in Plain Sight? Small Human-made Ponds, Emergent Insects, and Mercury Contamination of Biota in the Great Plains

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Abstract—Mercury (Hg) contamination of small human-made ponds and surrounding terrestrial communities may be 1 of the largest unstudied Hg-pollution problems in the United States. Humans have built millions of small ponds in the Great Plains of the United States, and these ponds have become contaminated with atmospherically deposited mercury. In aquatic ecosystems, less toxic forms of Hg deposited from the atmosphere are converted to highly toxic methylmercury (MeHg). Methylmercury is incorporated into the aquatic food web and then can be transferred to terrestrial food webs via emergent aquatic insects. The authors present a conceptual model that describes the movement of MeHg produced in aquatic ecosystems to terrestrial consumers via insects emerging from small human-made ponds. The authors hypothesize that pond permanence and the level of Hg contamination of the food web control this emergent insect-mediated flux of MeHg. The highest insect-mediated flux of MeHg is predicted to be from fishless semipermanent ponds with food webs that are highly contaminated with MeHg. Further development and testing of the conceptual model presented in the present column, particularly in the context of a changing climate, will require research at the regional, watershed, and pond scales. *Environ Toxicol Chem* 2015;34:1197–1205. © 2015 SETAC

Keywords—Mercury; Aquatic insect; Bioaccumulation; Environmental transport; Trophic transfer

Introduction

Humans have built millions of small ponds in the Great Plains of the United States over the last 100 yr [1], and all of these ponds receive mercury (Hg) deposited from the

atmosphere [2,3]). In aquatic ecosystems, less toxic forms of Hg deposited from the atmosphere are converted to highly toxic methylmercury (MeHg) [3–5]. Therefore, the construction of ponds has unintentionally created millions of MeHg-producing aquatic ecosystems that contaminate not only aquatic consumers but also emergent aquatic insects and the terrestrial consumers that feed on them, including spiders and birds [6–10]. In the present column we present a conceptual model that describes the movement of MeHg produced in aquatic ecosystems to terrestrial consumers via insects emerging from small human-made ponds in the Great Plains. We hypothesize that pond permanence and the level of Hg contamination of the food web control this emergent insect-mediated flux of MeHg. Mercury contamination of small human-made ponds and surrounding terrestrial communities may be 1 of the largest unstudied Hg-pollution problems in the United States. Our goal is to draw attention to this potentially important but unrecognized environmental issue that may affect the health of wildlife across the Great Plains and other agricultural areas of the United States where small human-made ponds are common.

Small Human-made Ponds in the Great Plains of the United States

Until recently, small ponds have been largely ignored by ecologists, and the study of small lentic systems has lagged behind larger-lake limnology over much of the past century [11] (but see Wilbur [12], Swingle [13], and Dendy [14]). Ponds are frequently omitted from descriptions of global cycles and processes, including carbon, energy and radiation, greenhouse gasses, nitrogen, oxygen, phosphorus,

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silicon, sulfur, and water [11]; and we here add Hg to this list. This oversight has likely resulted from a historical bias within the field of ecology to focus on “natural” over “human-made” ecosystems [15] and from an assumption that small ponds cover an insignificant surface area of the earth and are therefore unimportant in global processes [11]. However, recent inventories suggest that small ponds are more numerous than large lakes and that the spatial extent and surface area occupied by small ponds have been underestimated [11], leading some authors to argue that the importance of small ponds in global processes has not been appreciated [11,16].

The present column focuses on small human-made ponds (defined here to have surface areas smaller than ~1 ha [17]) in the Great Plains of the United States. Widespread pond construction in agricultural areas of the United States, like the Great Plains, is thought to have begun in the early twentieth century [1]. Small human-made ponds were constructed for a variety of purposes, including water supply for livestock, irrigation, sediment trapping and erosion control, and recreation [14,18]. Beginning in the 1940s and accelerating in the 1950s, large numbers of ponds were built with assistance from the Soil Conservation Service [1]. Swingle [13] estimated that the number of ponds in the United States increased from 20 000 in the 1930s to over 2 million by 1965. The total number of small human-made ponds is now estimated to be as high as 8 million to 9 million, making them the numerically dominant lentic water body type across the conterminous United States [1]. Eighty-five percent of the small ponds in the United States are less than 0.5 ha [18]. The eastern Great Plains has some of the highest densities of small ponds, with >3 ponds/km² (Figure 1); and the number of small ponds continues to increase at a rate of 1% to 2% per year in agricultural areas of the United States [16].

Human-made ponds are transient features of the landscape with average life spans in the Great Plains of less than 50 yr [1]. Most ponds are initially constructed so that they are deep enough to hold water throughout the year, even during periods of low rainfall. Once filled with water, new ponds are rapidly colonized by plants and animals and stocked with fish by humans. Throughout their existence, these small impoundments act as major sediment and carbon sinks because they trap inorganic and organic particles eroded from upstream terrestrial landscapes [1,18]. As these ponds age, sediment infilling slowly reduces the depth and volume of the basin, making these ponds more prone to drying and winter kill of fish. Eventually they begin to dry periodically during years with low rainfall but still contain water for long periods of time (months to years). Finally, late in the life of these ponds, sediment infilling reduces the water depth and basin volume to the point that these ponds contain water for only short intervals of time (weeks or months) during the year. Infilling with sediment is the dominant cause of pond disappearance in agricultural areas [1]. Humans can intervene in the ontogeny of ponds by removing sediment from older ponds, restoring

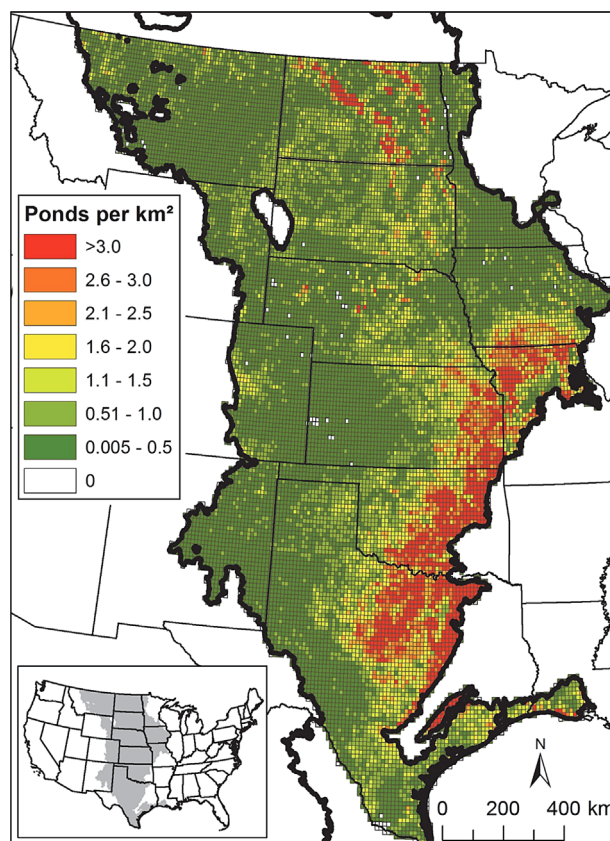


FIGURE 1: Density of small ponds (water bodies ≤ 1 ha) in 1:24-k quadrangles in the Great Plains ecoregion of the United States (hydrology data from the National Hydrology data set [64], ecoregion data from the US Environmental Protection Agency [65]). In the National Hydrology data set there are approximately 2 million small ponds in the Great Plains, with the highest densities of ponds in the east. In the eastern Great Plains ponds are found at densities of >3 ponds/km².

them to a permanent state in which they retain water throughout the year.

The ontogeny of ponds and associated change in pond permanence has significant implications for the biotic community structure within ponds. A number of ecologists have contributed to the development of a theoretical framework for understanding how communities in small aquatic ecosystems are shaped by permanence and predators [19–22]. In agreement with this theoretical framework, we have observed 3 general classes of human-made ponds in the Great Plains: 1) permanent fish ponds, 2) semipermanent fishless ponds, and 3) temporary fishless ponds (Figure 2). We define permanent fish ponds as those ponds that hold water over long periods of time (years). Permanent ponds do not dry and do not experience winter kill, allowing them to sustain fish populations [19,20]. Fish may be intentionally stocked for recreational purposes, or they may colonize ponds by migrating from upstream or downstream sources. Compared with fishless ponds, ponds with fish have insect communities that are less diverse and have lower biomass and smaller, less active taxa [19,20]. We define semipermanent fishless ponds as ponds that contain water over long periods (months to years) but do not contain fish because of periodic drying or

Animals Commonly Associated With Aquatic Food Webs in the Great Plains

The construction of small ponds by humans has increased biodiversity in the Great Plains by introducing aquatic food webs in upland areas where streams and natural lakes were not present. Animals commonly associated with aquatic food webs in the Great Plains include spiders (A, long-jawed orb weaver [*Tetragnatha* sp.]) crustaceans (B, water flea [*Daphnia* sp.]) insects (C, widow skimmer [*Libellula luctuosa*]; D, giant water bug [*Belostoma flumineum*]; E, black and yellow mud dauber [*Sceliphron caementarium*]; F, mosquito [*Aedes vexans*]), fish (G, bluegill [*Lepomis macrochirus*]), frogs (H, northern leopard frog [*Rana pipiens*]), turtles (I, red-eared slider [*Trachemys scripta*]), snakes (J, northern water snake [*Nerodia sipedon*]), birds (K, mallard [*Anas platyrhynchos*]; L, eastern phoebe [*Sayornis phoebe*]; M, great blue heron [*Ardea herodias*]; N, belted kingfisher [*Megaceryle alcyon*]; O, red-winged black bird [*Agelaius phoeniceus*]), and mammals (P, raccoon [*Procyon lotor*]). Because of their association with aquatic food webs, all of these animals could be contaminated with methylmercury.

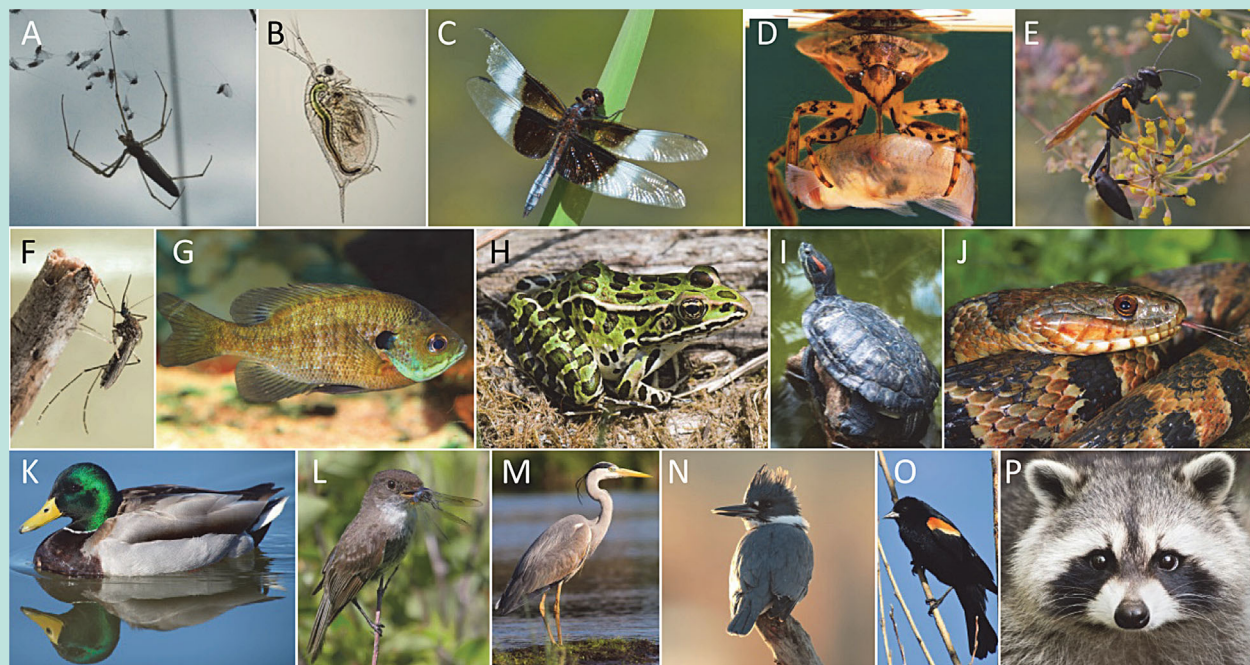
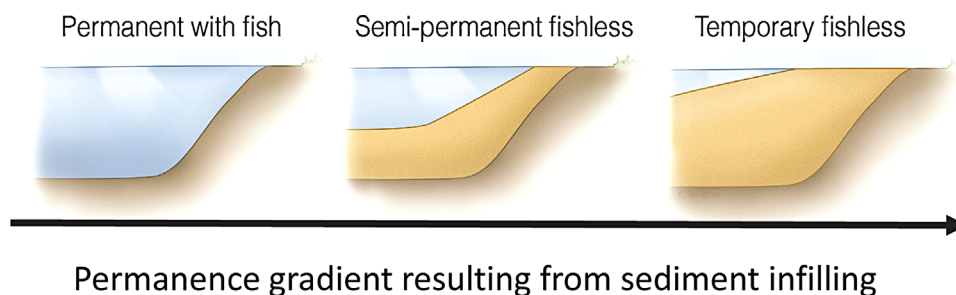


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winter kill. In semipermanent ponds without fish, large-bodied, active invertebrate predators like dragonflies replace fish as the top consumers in the food chain [19,20]. Semipermanent fishless habitats that perennially contain

water tend to support the highest diversity and overall abundance of large predatory insects [19]. We define temporary fishless ponds as ponds that hold water for only weeks at a time. Temporary ponds contain active, rapidly



Permanence gradient resulting from sediment infilling

FIGURE 2: Permanence gradient resulting from sediment infilling. Most small human-made ponds are initially constructed to hold water for long periods of time (years). As ponds age, sediment infilling causes them to become more shallow, and through time they change from permanent with fish to semipermanent without fish and eventually to temporary without fish.

developing taxa and fewer predators than do semipermanent fishless ponds that hold water over longer periods (months to years) [20]. Temporary fishless ponds have especially diverse beetle and midge communities [19]. Because fish and invertebrate predators are excluded, temporary ponds are unique in that mosquito larvae can be the numerically dominant residents [19]. This view of the relationship between insect communities, pond permanence, and predators is idealized and simplified [20]; but it captures the essential features of the biotic communities that inhabit ponds during their ontogeny. It should be noted that these categories represent points along a dynamic continuum rather than fixed states. Not only does sediment infilling affect permanence over decades but unusually wet or dry years can cause ponds to shift from 1 class to another.

Because pond permanence influences aquatic community structure, permanence also influences insect emergence [9,10] and the potential effects of emergent insects on the surrounding terrestrial environment [23–25]. Insect emergence differs with the class of pond [9,10]. For example, in permanent fish ponds with centrachids that feed selectively on large invertebrate prey [26], the biomass of emerging dragonflies can be suppressed to the point that it is relatively similar to the biomass of emerging small-bodied insects, like chironomids and mosquitoes [9]. In semipermanent ponds without fish, the biomass of emerging dragonflies can be much greater than that of small-bodied chironomids and mosquitoes [9]. In temporary ponds without fish, only chironomids and mosquitoes emerge if water retention time is too short for dragonfly life cycles [19,27]. Because the insect taxa that emerge from ponds vary by class of pond, the species of terrestrial consumers that are recipients of organic carbon contained in the tissues of emergent insects will also vary with class of pond. For example, higher densities of insectivorous birds are found around fishless ponds with high mayfly emergence than around fish ponds with low mayfly emergence [25]. The class of pond may also indirectly affect terrestrial community structure. Knight et al. [23] found that plants near ponds that contain fish receive more pollinator visits and are less pollen-limited than plants near fish-free ponds because dragonflies that emerge from fish-free ponds consume insect pollinators and alter pollinator foraging behavior.

Mercury Contamination of the Great Plains

Mercury cycle

Mercury contamination of the environment is hazardous to wildlife health [3,28,29]. Wildlife are primarily exposed to MeHg through the consumption of Hg-contaminated prey [29], and relatively low doses can have adverse effects on wildlife health and reproduction [3,28,29]. Recent findings indicate that the scope and severity of the Hg problem for wildlife have been substantially underestimated, and the

ecotoxicology of Hg is an area of active research [28]. For example, terrestrial songbirds have been found to consume MeHg-contaminated prey [30], and songbirds exposed to MeHg may suffer reduced reproductive success [31].

All areas of the earth have elevated levels of Hg as a result of widespread atmospheric deposition from anthropogenic sources [3,4]. Mercury deposition rates are estimated to have increased by a factor of 3 to 5 since the industrial revolution [4] and by a factor of 7 to 10 since antiquity [32]. Today the largest anthropogenic sources of environmental Hg are atmospheric emissions from fossil fuel combustion and small-scale gold mining in developing countries [32]. Mercury is released into the atmosphere, where it can reside for up to 1 yr until being deposited onto the earth's surface, often far from the source [3,4]. In general, Hg deposited on terrestrial surfaces exists in a nonbioaccumulative and relatively nontoxic inorganic form [3–5]. Once deposited on the terrestrial landscape, Hg can bind strongly to organic matter; and Hg in soil represents the largest pool of Hg in the terrestrial environment [3,4]. Soil-bound Hg can be transported to ponds in runoff, where microbes can convert it to the highly toxic and bioaccumulative form MeHg [3–5]. Organisms at the base of the food web, such as phytoplankton and periphyton, concentrate MeHg directly from the water [33,34], whereas consumers are exposed to MeHg primarily through their diets [35–37].

Contaminants, like MeHg, that enter aquatic food webs have the potential to be transferred to terrestrial food webs when aquatic insects that spend part of their life cycle in aquatic ecosystems emerge as adults [6,9,38–42]. For each taxon of emergent insect within a water body, the flux of MeHg moving from aquatic to terrestrial ecosystems is a product of the taxon's MeHg concentration and emergent biomass [9,10]. In general, the MeHg concentration of a given taxon is determined by the taxon's position in the food web. Insect taxa with low trophic positions, such as periphyton-grazing caddis flies and chironomids, have relatively low MeHg concentrations, whereas carnivorous damselflies and dragonflies have relatively high MeHg concentrations [6,9,10].

Conceptual Model of Insect-mediated Flux of MeHg From Small Human-made Ponds in the Great Plains

We hypothesize that MeHg flux of emergent insects from small human-made ponds is controlled by the interaction of 2 major factors: pond permanence and the level of Hg contamination of the food web (Figure 3). As ponds age, sediment infilling causes them to become more shallow, and through time they change from permanent with fish to semipermanent without fish and eventually to temporary without fish. Our research has shown that the presence or absence of fish regulates insect emergence and the associated

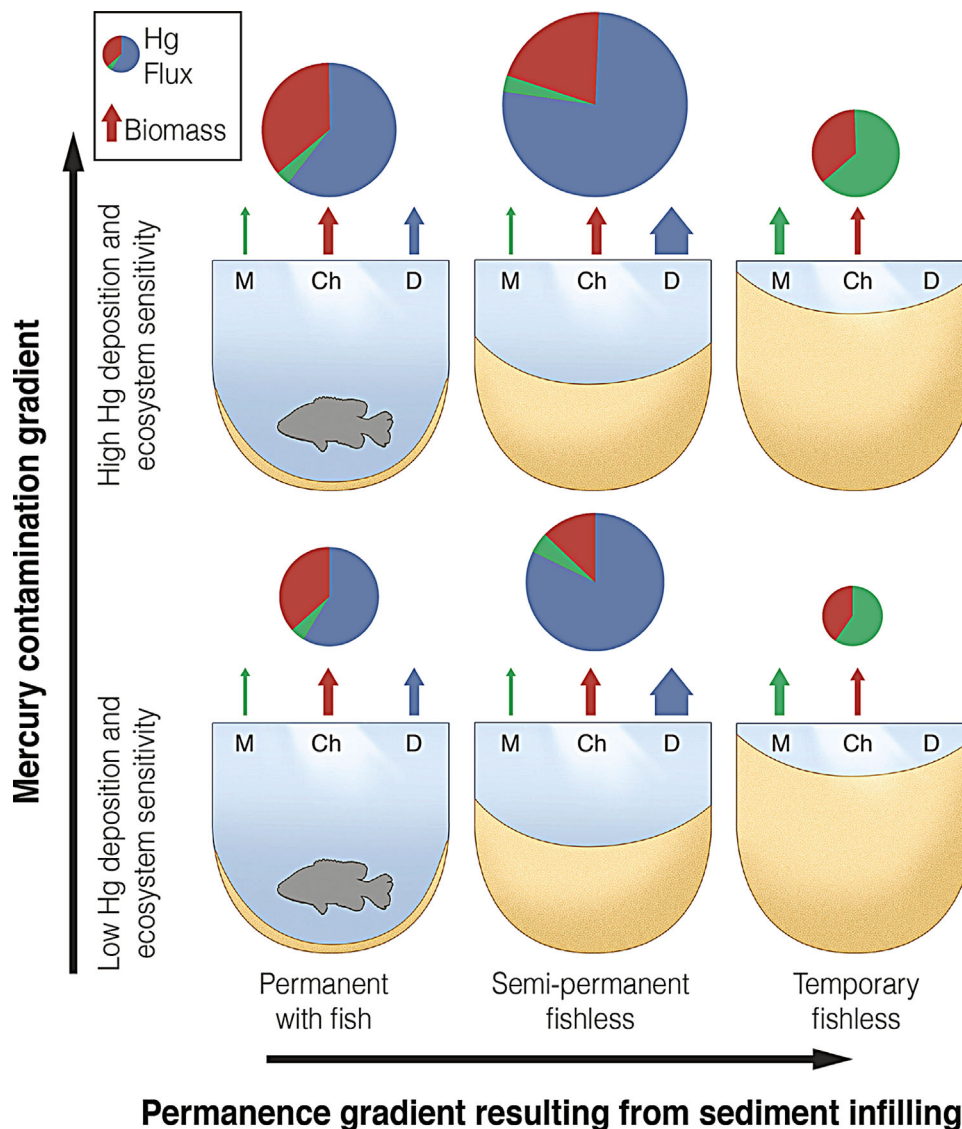


FIGURE 3: Methylmercury (MeHg) flux in emergent insects is controlled by the interaction of 2 major factors: pond permanence and the level of Hg contamination of the food web. In general, Hg contamination of the food web is controlled by atmospheric Hg deposition and ecosystem sensitivity to Hg. The thickness of the arrows above the ponds indicates the relative biomass of emerging insects. The pie diagrams indicate relative MeHg flux. Mosquitoes (M) and chironomids (Ch) are presented as examples of small taxa, and dragonflies (D) are presented as an example of a large taxon. This figure presents a “snapshot” of relative MeHg flux during a period when all 3 pond types contain water. This illustration does not take into account dry periods (when there would be no emergence) and therefore does not reflect annualized MeHg flux for the 3 pond types.

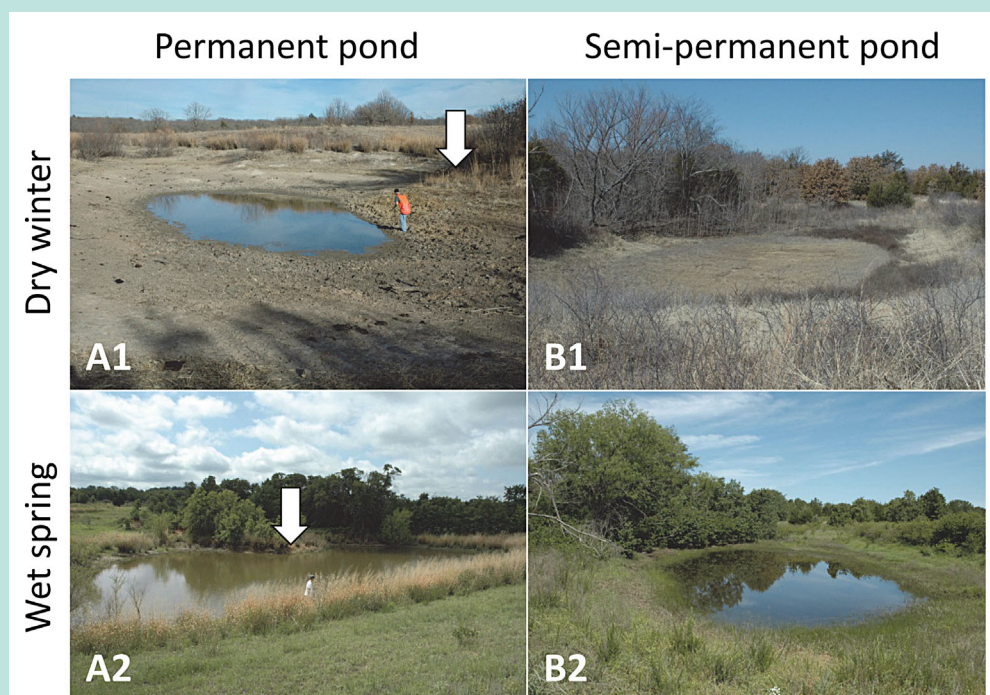
MeHg flux [9,10]. In permanent ponds with fish, the biomass of small taxa (e.g., chironomids and mosquitoes) and large taxa (e.g., dragonflies) that emerge may be relatively similar [9]. However, large taxa would contribute more to the flux because their MeHg concentrations are higher [9]. In semipermanent fishless ponds, dragonfly biomass may be considerably larger than chironomid and mosquito biomass in the absence of fish. Dragonflies would account for a large percentage of the total MeHg flux in a semipermanent fishless pond because of their high biomass coupled with a high MeHg concentration. The elevated biomass of highly MeHg-contaminated dragonflies would also result in a higher MeHg flux from semipermanent ponds compared with permanent ponds with fish. In temporary fishless ponds, only insects with very short life cycles such as chironomids

and mosquitoes could become adults and emerge. The MeHg flux from temporary fishless ponds would be less than the flux from permanent or semipermanent ponds because of the absence of predatory insects.

We hypothesize that the amount of MeHg flux for any class of pond is also determined by the degree of Hg contamination of the food web [9] (Figure 3). In the Great Plains, the primary source of Hg to ponds is atmospheric deposition. There is a longitudinal gradient in wet Hg deposition across the Great Plains, with Hg deposition in the east being up to 7 times greater than Hg deposition in the west in some years [43]. Although atmospheric deposition is the primary source of Hg to most aquatic systems [3,4] and Hg deposition is correlated with Hg contamination of the food chain [44–46],

Water-Level Fluctuations and Hg Contamination of Small Human-Made Ponds: An Example of a Factor Associated With Ecosystem Sensitivity to Atmospheric Hg Deposition

Permanent, semipermanent, and temporary ponds in the southern Great Plains experience extreme annual water-level fluctuations, resulting in most of the pond bottom being exposed during dry periods beginning in the late summer and then rewetting as a result of spring rainfall. Because the basins of human-made ponds are shallow, even a permanent pond that maintains enough water to allow fish to survive during dry periods may have the majority of its sediment exposed during parts of the year. Two small human-made ponds in north Texas are shown to illustrate the extreme water-level fluctuations in permanent (A) and semipermanent (B) ponds during a dry winter (A1, B1) and a wet spring (A2, B2). Because the pictures of the permanent pond (A1, A2) were taken from 2 different perspectives, a peninsula in the permanent pond is marked with a white arrow to facilitate comparison. This annual cycle of drying and rewetting would be expected to create anoxic, carbon-rich conditions conducive to Hg-methylating bacteria in all pond types [5,59]. Indeed, several studies have reported a correlation between water-level fluctuation and MeHg concentrations in biota [59–63]. Because large areas of sediment are exposed annually, we hypothesize that all categories of small human-made ponds in the Great Plains would be sensitive to atmospheric Hg deposition; but we would not expect pond types to differ in the level of food web contamination. In support of this hypothesis we found that invertebrate taxa found in both permanent and semipermanent ponds had elevated, but similar Hg concentrations [8].



atmospheric deposition of Hg is not the only determinant of food chain contamination. Some aquatic ecosystems are classified as Hg-sensitive because seemingly small inputs of Hg from the atmosphere can cause significant MeHg contamination of fish and wildlife [47]. Factors associated with ecosystem sensitivity to atmospheric Hg deposition include forests and wetlands within the watershed, shallow water flow paths into the ecosystem, elevated dissolved organic carbon, low productivity, low pH, and water-level fluctuations [48,49]. Therefore, ponds receiving elevated Hg deposition and/or those with characteristics associated with Hg sensitivity would have more contaminated food webs and would be hypothesized to have elevated MeHg flux in emergent insects (Figure 3).

Future Research on Emergent Insect-mediated Flux of MeHg From Small Human-made Ponds in a Changing Climate

Climate change in the Great Plains

The Great Plains is characterized by strong seasonal climate variations with recurring periods of extended drought (such as the Dust Bowl of the 1930s) alternating with wetter conditions [50]. Significant trends in regional climate are apparent over the last few decades, with increases in average temperatures throughout the Great Plains region [50].

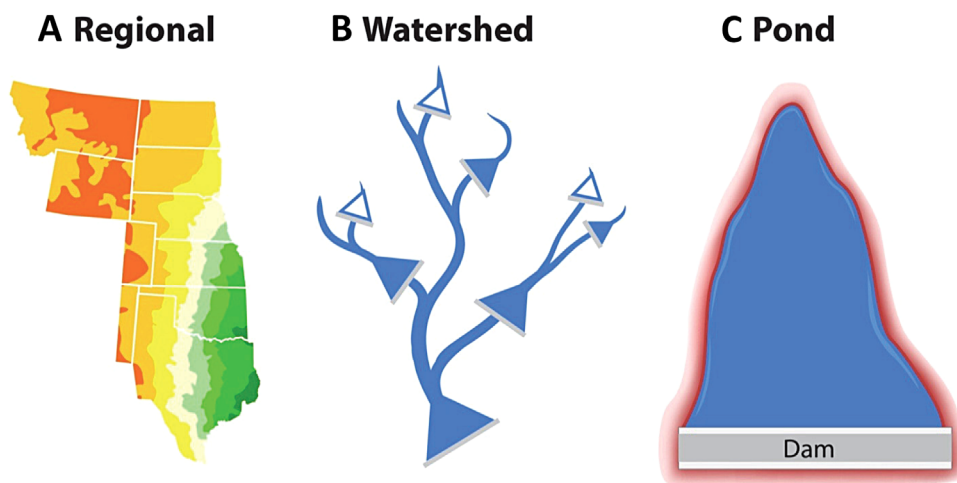


FIGURE 4: Further development and testing of the conceptual model presented will require research at regional, watershed, and pond scales. For example, (A) precipitation patterns vary longitudinally across the Great Plains (figure modified from Bonnin et al. [51]), which may influence patterns of Hg deposition and pond permanence. (B) The distribution of pond types within a watershed may change as a function of watershed position and may influence patterns of methylmercury (MeHg) flux in a watershed. Open and closed symbols represent temporary or semipermanent and permanent ponds, respectively. (C) Methylmercury originating from emerging insects would be most concentrated near the shoreline and decrease in concentration with distance from the pond, as indicated by the intensity of the red outline.

Temperatures are projected to continue to increase across the Great Plains over this century, and conditions are anticipated to become wetter in the north and drier in the south [50]. Projections of increasing temperatures, faster evaporation rates, more sustained droughts brought on by climate change [50], and human attempts to adapt to the changing climate will likely alter the proportion of permanent, semipermanent, and temporary ponds.

Future research

Further development and testing of the conceptual model presented in the present column, particularly in the context of a changing climate, will require research at the regional, watershed, and pond scales (Figure 4). Below we present examples of hypotheses that need further investigation to develop models predicting emergent insect-mediated flux of MeHg from ponds in the Great Plains and how MeHg flux may be altered by climate change.

Regional scale

Because rainfall patterns and drought susceptibility vary from west to east across the Great Plains, we hypothesize that there will be longitudinal differences in the proportion of permanent, semipermanent, and temporary ponds. For example, we predict that the greatest abundance of permanent ponds will be in the eastern Great Plains where rainfall is highest [51] (Figure 4A). Factors that may impact insect-mediated flux of MeHg by altering food web contamination of ponds, including wet Hg deposition [43] and landcover [52], also vary longitudinally across the Great Plains. These factors may interact to produce complex spatial patterns of insect-mediated flux of MeHg. An understanding of these spatial patterns will be necessary to predict the effect of climate change on Hg contamination of the Great Plains.

Watershed scale

In the Great Plains, we hypothesize that the distribution of pond types within a watershed changes as a function of watershed position and may influence patterns of MeHg flux within a watershed. Smaller temporary and semipermanent ponds may predominate in the upstream portion of watersheds, where low-order streams often have intermittent flow [53] (Figure 4B). The abundance of larger permanent ponds may be greater in downstream portions of watersheds where drainage areas are larger and stream order is higher [54] (Figure 4B). As ponds age, pond permanence may change along the watershed gradient such that the location of temporary and semipermanent ponds may shift to lower positions in the watershed. Reduction of surface runoff predicted by climate change models for the southern Great Plains [50] could further alter the abundance and location of temporary and semipermanent ponds in watersheds.

Pond scale

We hypothesize that the influence of MeHg flux on terrestrial food webs varies with distance from the shoreline. We would expect that MeHg originating from emerging chironomids would be most concentrated near the shoreline and decrease in concentration with distance from the pond (Figure 4C), as has been found for carbon [24,55]. After emergence, dragonflies disperse greater distances than chironomids; and some migratory species may transport MeHg hundreds of kilometers away from the pond where the Hg was methylated [56].

Conclusion

The earth is now in an era of unprecedented global-scale changes caused by human activities [57]. Evidence is

mounting that environmental stressors, like pollution, climate change, and habitat alteration, exhibit strong interactions with each another as drivers of global-scale changes [58]. Therefore, our understanding of environmental Hg contamination in the Great Plains and other regions needs to be based on studies of Hg pollution in the context of climate change and habitat alteration, which includes the construction of small human-made ponds [32].

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Data Availability

Data from the present column are available on request from M. Chumchal (m.m.chumchal@tcu.edu).

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