GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G49427.1

Manuscript received 23 June 2021
Revised manuscript received 25 September 2021
Manuscript accepted 2 October 2021

Published online 15 December 2021

The importance of oxbow lakes in the floodplain storage of pollutants

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ABSTRACT

Oxbow lakes are important stores for fine-grained sediment, which potentially makes them critical sinks for sediment-associated pollutants. We leverage an exhaustive public archive of coring data, supplemented by our data collection, to provide a quantitative assessment of the role of oxbows as off-channel sinks. We investigated loading trends of sediment-sorbed polychlorinated biphenyls (PCBs) within oxbows of the Housatonic River, an actively meandering river in western Massachusetts, USA. Our results reveal the efficiency of oxbows as sinks, with average PCB concentrations (14.8 ppm) that are nearly twice that of the surrounding floodplain (7.56 ppm). Even though the 5.83 km^2 floodplain is the largest sink of PCB-laden material, storing as much as 14.1 t of PCBs or 2.42 g m^{-2}, oxbows store more than 20% of all PCBs (3.63 t of PCBs or 11.2 g m^{-2}) while making up just over 5% of the floodplain surface area. Nearly 85% of the oxbow storage of PCBs occurs within the first 50 m of floodplain, making clear the significance of regular oxbow production to the off-channel storage of sediment-associated pollutants.

INTRODUCTION

Oxbow lakes are some of the most widespread and distinctive landforms along meandering rivers. Their presence indicates that, at least for some period, river meandering occurred at rates sufficient for neck cutoff or that floods were able to generate meander-scale avulsions in the form of chute cutoff (Constantine and Dunne, 2008; Constantine et al., 2010; Zinger et al., 2011). Oxbows can persist for centuries as aquatic floodplain habitat while gradually filling with wash and suspendable load supplied during floods, eventually becoming fine-grained plugs that can subsequently limit meandering (Hudson and Kesel, 2000; Munoz et al., 2018). The environmental consequence of alluviation by fine sediment is that oxbows may be principal sinks for sediment-associated pollutants in meandering river floodplains. Although recent work has identified the storage of heavy metals and organic pollutants in oxbows, their importance as off-channel sinks has remained unclear (Balogh et al., 2017; Ciazela et al., 2018).

The lasting contamination of the meandering Housatonic River within westernmost Massachusetts, United States, provides a rare opportunity for assessing the relative importance of oxbows in the floodplain storage of pollutants. From 1932 to 1977 CE, the floodplain of the Housatonic River was the site of a General Electric (GE) Company facility that used polychlorinated biphenyls (PCBs) in the production of capacitors and transformers (Eitzer, 1993). Estimates suggest that 18–680 t of PCBs were released directly into the river and floodplain landfills (Moore, 1998). Significant concentrations (>800 ppm) have been found adsorbed to material in suspension and within the riverbed (Frink et al., 1982; Bedard et al., 1998). For context, the U.S. Environmental Protection Agency (EPA) in 2014 set a 50 ppm limit for the permittable disposal of PCB-laden waste in landfills and a 10 ppm limit for PCBs in the soils of recreational areas. Sediments collected by federal agencies from the riverbed and floodplain included samples from oxbow lakes (Weston Solutions, Inc., 2002). These samples have been analyzed for PCBs, and the data have been archived by the EPA and the U.S. Army Corps of Engineers (USACE), representing what is perhaps one of the most exhaustive data sets on the storage of contaminants throughout the floodplain of an actively meandering river. We report our synthesis of these data, supplemented by our own data collection. Our results demonstrate the role of oxbows as sinks for pollutant-laden sediment. The work also highlights the importance of oxbow production to river-floodplain ecosystem services (benefits that natural ecosystems generate for society) and to the geomorphic connectivity of floodplains (Heckmann et al., 2018; Wohl et al., 2019; Stammel et al., 2020; Zhou and Endreny, 2020).

GEOMORPHIC SETTING

The Housatonic River drains 5050 km^2 of southwestern New England and portions of eastern New York, the homeland of the Stockbridge–Munsee Band of Mohican peoples (Fig. 1A). Our study reach, with a sinuosity of 1.56, extended for 16 river km from the confluence of the east and west branches of the river near Pittsfield, Massachusetts (42.433665°N, 73.251030°W), to 1.5 river km upstream of Woods Pond Dam (42.347151°N, 73.244981°W), a low-head dam near Lenoxdale, Massachusetts (Fig. 1A). The GE facility that was the main source of PCB contamination was sited along the right bank of the east branch, ~3 river km upstream from the confluence. Between 1913 and 2019, mean annual discharge equaled 15.2 m^3 s^{-1} (U.S. Geological Survey [USGS] gauge 01197500), and the 2 a and 10 a annual maximum discharges equaled 105.6 m^3 s^{-1} and 180.7 m^3 s^{-1}, respectively (USGS gauge 01197500). From 1978 to 1996, the median concentration of suspended sediments (USGS gauge 01197500) was 5.77 mg L^{-1} (first quartile, 3.64 mg L^{-1}; third quartile, 12.4 mg L^{-1}), which is comparable to that of other New England rivers of similar

CITATION: Thomas, S.-S., et al., 2022, The importance of oxbow lakes in the floodplain storage of pollutants: Geology, v. 50, p. 392–396, https://doi.org/10.1130/G49427.1

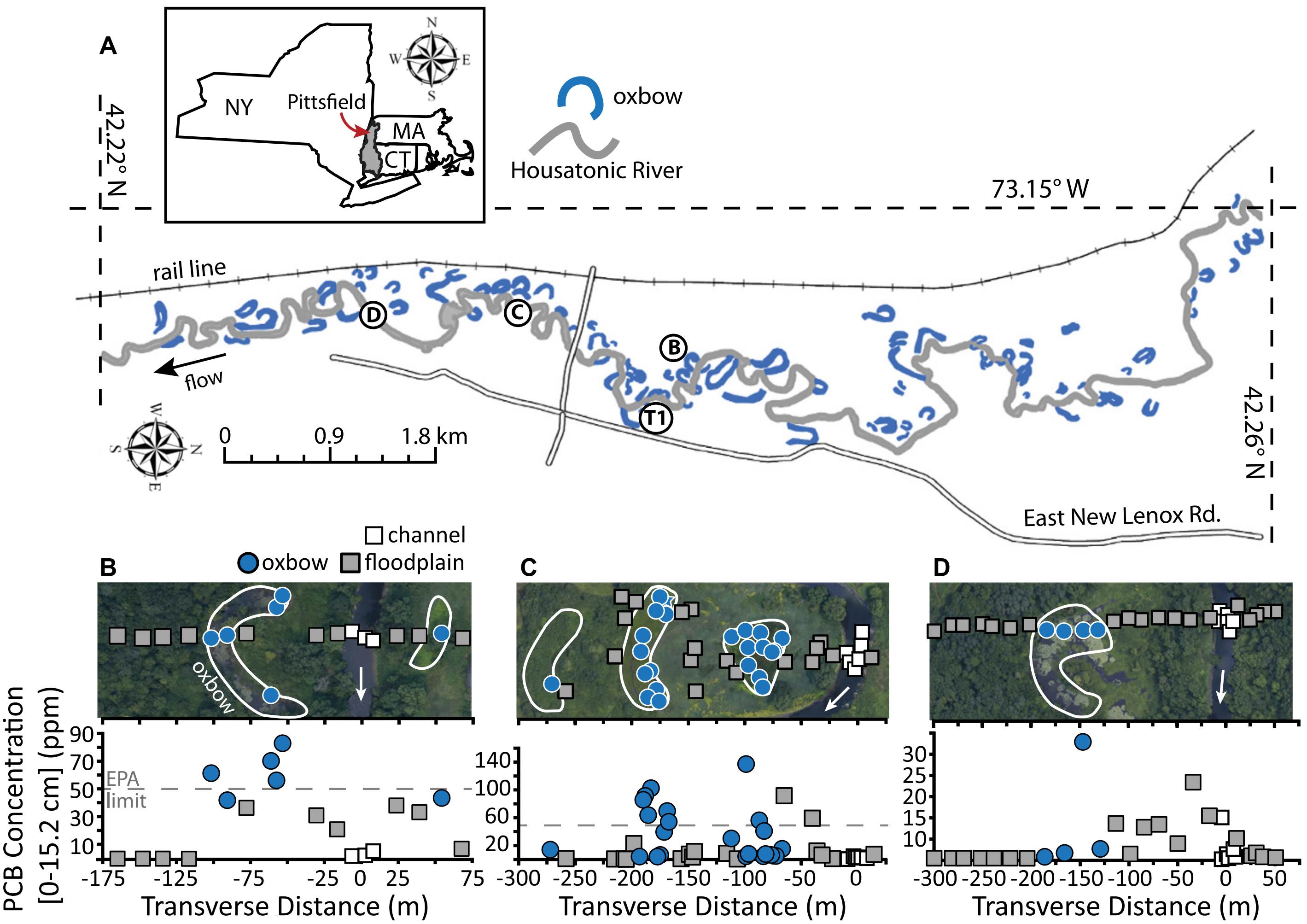

Figure 1. (A) Location map of the study reach and watershed of the Housatonic River, western Massachusetts, USA. The location of Pittsfield, Massachusetts, is shown in the inset. Locations of archival transect data are identified as B, C, and D. Location of our coring transect is identified as T1. (B,C,D) Maps of coring locations and polychlorinated biphenyl (PCB) concentrations within the shallow subsurface for the riverbed (channel), floodplain, and oxbow sites. Flow direction is indicated by white arrows. The U.S. Environmental Protection Agency (EPA) limit of 50 ppm for the permittable disposal of PCB-laden waste is denoted by gray dashed lines.

drainage (Campo et al., 2003). Between 30% and 94% of these suspended sediments were finer than 0.062 mm (Bent, 2000). Although the study reach is bounded by Woods Pond Dam, it is devoid of flow impoundments, and riverbank protection is largely absent along its length. Based on georeferenced air photographs (1941–2018; provided by the Massachusetts Bureau of Geographic Information), annual average migration can be as high as 0.31 m a^{-1} for individual meanders. One hundred (100) oxbows, ranging in size from 287 m^2 to 15700 m^2, and with an average surface area of 3590 m^2 (3130 m^2, $\pm$ 1σ), have been identified from aerial photographs and lidar-derived floodplain topography provided by the Massachusetts Bureau of Geographic Information.

METHODS

The data archive was a product of sediment coring sponsored by the EPA and the USACE in 1998 and 1999 (Weston Solutions, Inc., 2002). Cores were collected along transects oriented perpendicular to riverbanks that encompassed the extent of floodplain inundated by an event with a 10% annual exceedance probability. Within the study reach, 447 sediment samples were retrieved from 17 transects (spaced 457 m apart), including from 46 oxbow lakes. In all cases, samples were aggregated based on depth intervals: from the surface to 15.2 cm (hereafter shallow subsurface) and from 15.2 cm to 30.5 cm (hereafter deeper subsurface). Total PCB concentrations from subsamples of the aggregates were determined using EPA Method 8082A (Weston Solutions, Inc., 2002). Grain-size fractions for all aggregated samples were determined as percent gravel, sand, silt, and clay by sieving (Weston Solutions, Inc., 2002). Total organic content (TOC) for all aggregated samples was determined through the dry combustion and detection of evolved CO_2. To provide for valley-wide characterizations, we binned oxbow and floodplain data within 25-m-wide increments away from the riverbank. Two-tailed *t*-tests and two-tailed Mann-Whitney tests were used to assess the significance of differences in the populations of all measurements. Spearman's rank correlation coefficients and *t*-tests of correlation were used to determine the significance of correlations.

To determine the fraction of pollutant mass stored within each alluvial setting, we converted the binned concentrations in the shallow and deeper subsurface into mass of stored PCBs using the following equation:

$$M_{a,i} = C_{a,i}\rho_b A_{a,i}, \qquad (1)$$

where the subscript a denotes an oxbow (oxb) or floodplain (fld) variable, the subscript i denotes bin increment, M is the total mass of PCBs (kg) within a depth interval, C is the average concentration of PCBs (kg kg^{-1}), ρ_b is the bulk density of sediment equal to 1400 kg m^{-3} (roughly equivalent to silty loam), and A is the total surface area (m^2). We determined $A_{oxb,i}$ by binning oxbows according to their first

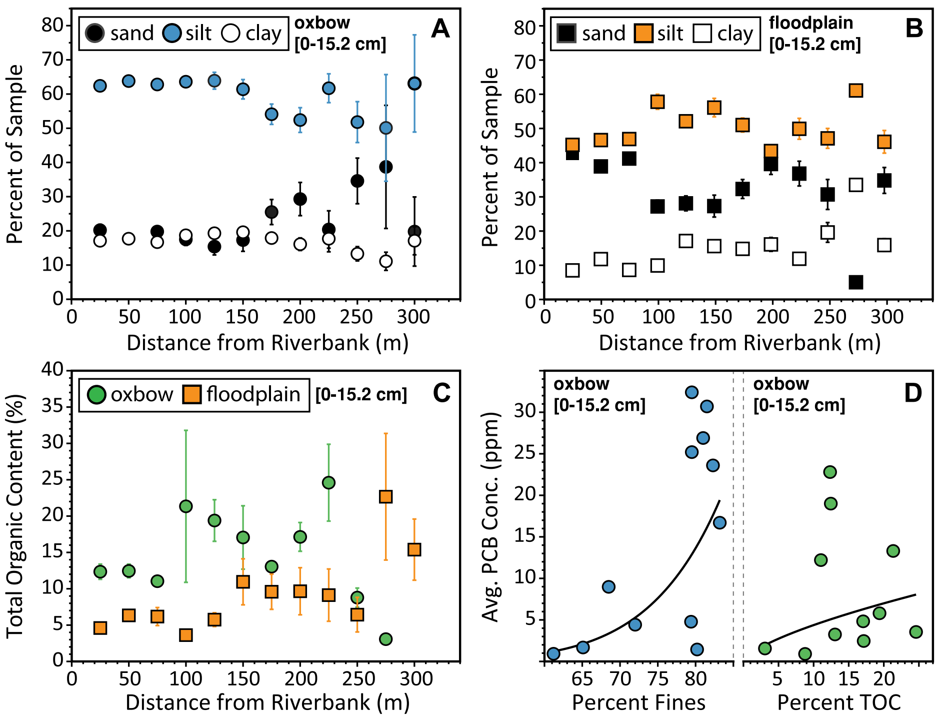

Figure 2. (A,B) Granulometric data for archival oxbow and floodplain samples of the shallow subsurface of the Housatonic River, western Massachusetts, USA. Data points represent averages within 25 m bins, and error bars represent ±1 standard error. (C) Average values of total organic content (TOC) within 25 m bins measured using archival samples of the shallow subsurface. Error bars represent ±1 standard error. (D) Average polychlorinated biphenyl (PCB) concentrations (C_{oxb}) within 25 m bins for archival oxbow samples of the shallow subsurface plotted against the average percent of fines (silt + clay) (F) and average total organic content (T_{carb}). Trendlines represent power functions for F ($R^2 = 0.50$) and T_{carb} ($R^2 = 0.14$).

spatial occurrence, and $A_{fld,i}$ using the following equation:

$$A_{fld,i} = 2bV - A_{oxb,i}, \qquad (2)$$

where b is bin width (25 m), V is valley length of the study reach (10.3 km), and d is depth (m). The total mass of stored PCBs for each alluvial setting per bin was determined by summing solutions to Equation 1 for each depth interval.

We conducted a floodplain coring survey to supplement the EPA and USACE archive. Samples were collected along a transect (Fig. 1A) using a percussion corer fitted with polycarbonate tubes. Analyses of PCBs involved sediment extractions at 7.6 cm increments following EPA Method 8082A. Subsamples were also analyzed for grain-size characteristics by hydrometer and for organic content by loss-on-ignition (LOI). Selected subsamples extracted at 2.54 cm increments were analyzed for activities of excess ^{210}Pb (through ^{226}Ra) and ^{137}Cs via gamma emission counting at the Watershed Processes and Short-Lived Isotopes Lab at Dartmouth College (New Hampshire, USA) (Landis et al., 2012, 2014).

RESULTS AND DISCUSSION

The archival data highlight the role of oxbows as sinks for PCB-laden sediment (Figs. 1B–1D). Previous work documented the tendency for PCB to adsorb onto fine sediment and organic particles (Steen et al., 1978; Huang et al., 2018). Oxbow deposits are significantly finer than deposits on the surrounding floodplain (t-test: $\alpha < 0.001$; Mann-Whitney: $\alpha < 0.05$), with fines (silt + clay) in oxbow deposits averaging 76.1% (26.0%, $\pm 1\sigma$) and in floodplain deposits 65.6% (26.0%, $\pm 1\sigma$) (Figs. 2A and 2B). Oxbows are significantly enriched in TOC (t-test: $\alpha < 0.001$; Mann-Whitney: $\alpha < 0.01$), with TOC in oxbow deposits more than double that of floodplain deposits, averaging 16.5% (17.3%, $\pm 1\sigma$) and 7.22% (9.18%, $\pm 1\sigma$), respectively (Fig. 2C). Although oxbow data are sparse in the distal floodplain, the observed reduction in fines and TOC within distal oxbow deposits may indicate a spatial limit to loading by overbank flows or to the influence of internal floodplain drainage (Mertes, 1997; Goodbred and Kuehl, 1998; Czuba et al., 2019; Juez et al., 2019). PCB concentrations within oxbow deposits correlate positively and significantly with the prevalence of fines (Spearman's: $\alpha < 0.05$; t-test: $\alpha < 0.05$) but not with TOC (Spearman's: $\alpha > 0.65$; t-test: $\alpha > 0.60$) (Fig. 2D).

Our coring data compare well with the archive, which highlights the importance of fine-grained sediment loading. The radiometric profile of the proximal floodplain for excess ^{210}Pb contrasts with the profile of oxbow deposits (Fig. 3B). The steeper and more penetrating profile of the proximal floodplain may reflect the effects of rapid sedimentation or extensive reworking (Goodbred and Kuehl, 1998; Zhang et al., 2015). Conversely, the oxbow profile of excess ^{210}Pb may reflect slower and more episodic sedimentation (Goodbred and Kuehl, 1998; Aalto et al., 2008). The profiles of ^{137}Cs are similarly indicative (Fig. 3B), with the oxbow profile depicting a peak in deposition in 1963 CE, whereas the proximal floodplain indicates extensive reworking. Assuming no mixed-layer depth, an annual average oxbow sedimentation rate of 0.36–0.42 cm a^{-1} can be calculated from the ^{137}Cs data using either 1954 as the onset of fallout or 1963 as the year of peak fallout, which is comparable to ^{137}Cs archive data

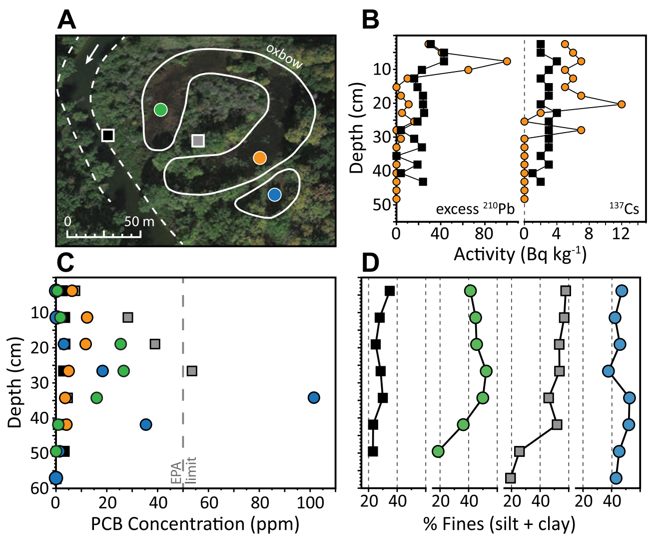

Figure 3. (A) Map of coring locations of transect T1 on the Housatonic River, western Massachusetts, USA (see Fig. 1 for location of T1). Squares indicate locations of proximal (black) and distal (gray) floodplain cores. Circles indicate locations of oxbow cores. Colors distinguish cores, the data from which are plotted in panels B, C, and D. Coordinates of coring locations are provided in the Supplemental Material (see footnote 1). (B) Radiometric profiles for both the proximal floodplain core (black squares) and oxbow core (orange circles) of ^{210}Pb and ^{137}Cs. (C) PCB concentrations with depth for all cores, the locations of which are indicated by the shapes and colors of symbols in panel A. The U.S. Environmental Protection Agency (EPA) limit of 50 ppm for the permittable disposal of PCB-laden waste is denoted by the gray dashed line. (D) Percent of fines (silt + clay) with depth for sediment cores (ordinate values are the same as those in panel C).

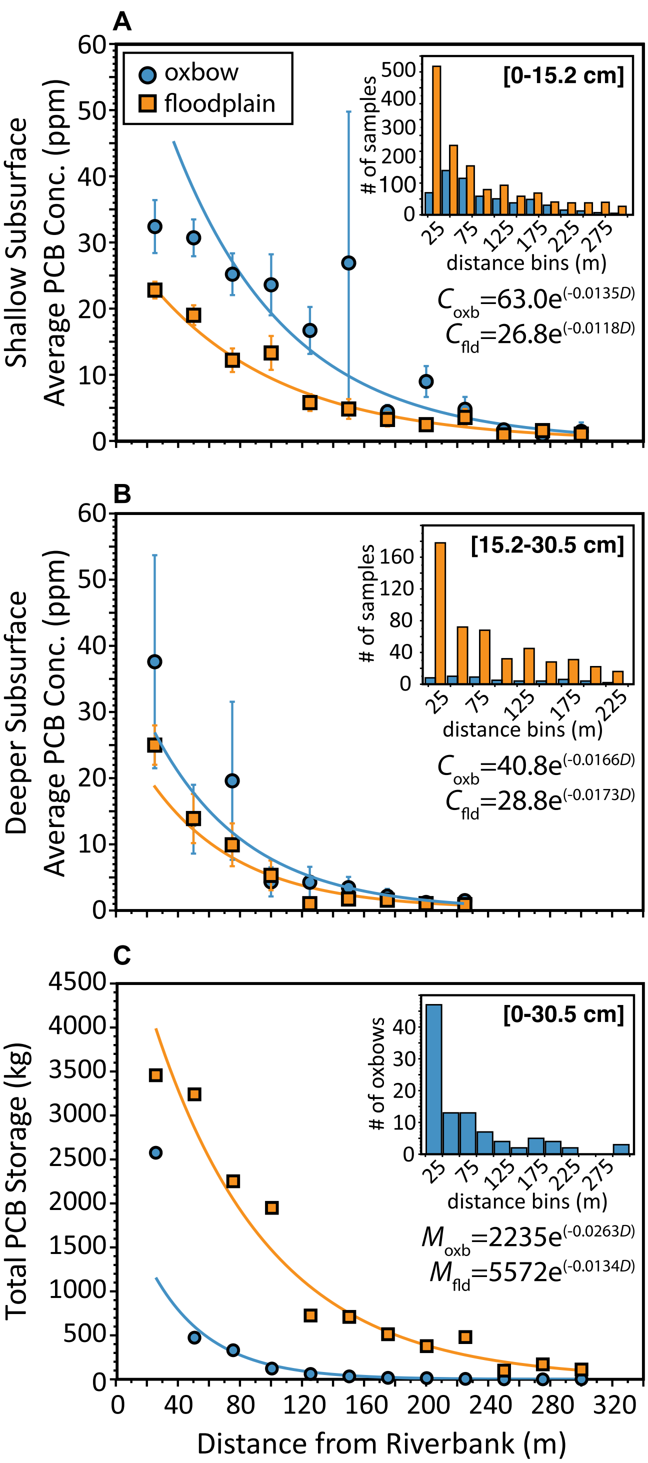

Figure 4. (A,B) Average polychlorinated biphenyl (PCB) concentrations of archival samples of the shallow and deeper subsurface of the Housatonic River, western Massachusetts, USA. Error bars represent ±1 standard deviation. Inset graphs indicate the number of samples per alluvial setting within each bin. Equations describe exponential trendlines fit to the shallow subsurface and deeper subsurface of the oxbow (R^2 = 0.86, R^2 = 0.91, respectively) and floodplain (R^2 = 0.93, R^2 = 0.86, respectively) samples, where D is distance from riverbank (m). The variables M_{oxb} and M_{fld} define the mass of stored PCBs within oxbows and the floodplain, respectively. (C) Estimates of the total mass of PCB storage within each bin are based on Equation 1. Inset graph indicates the number of oxbows within each bin. Equations describe exponential trendlines fit to the oxbow (R^2 = 0.97) and floodplain (R^2 = 0.94) data.

for Woods Pond (Fig. S1 in the Supplemental Material[1]) (DeLaune et al., 1978; Goodbred and Kuehl, 1998). Sedimentation may be fastest in the proximal floodplain, but the lack of fines (23.1–34.8%) appears to have prevented significant PCB storage (2.24–3.85 ppm) (Figs. 3C and 3D). The distal floodplain core located 50 m from the river's edge contains significant concentrations of PCBs (0.048–53.5 ppm) due to the significant presence of fines (19.3–57.9%) (Figs. 3C and 3D). LOI estimates of organic content vary from 5.30% (1.68%, ± 1σ) in the proximal floodplain to 13.1% (10.6%, ± 1σ) in the more distal floodplain to 7.83% (4.39%, ± 1σ) in the oxbow deposits (Fig. S2).

Binned PCB concentrations throughout the study reach indicate the importance of oxbows in off-channel contaminant storage. PCB concentrations within the shallow subsurface of oxbow deposits are significantly greater than those of the surrounding floodplain (t-test: $\alpha < 0.05$; Mann-Whitney: $\alpha < 0.2$) (Fig. 4A) and average 14.8 ppm (12.4 ppm, ± 1σ) and 7.56 ppm (7.46 ppm, ± 1σ), respectively. However, PCB concentrations within the deeper subsurface of oxbow deposits are statistically indistinguishable from those of floodplain deposits (t-test: $\alpha > 0.50$; Mann-Whitney: $\alpha > 0.50$) (Fig. 4B) and average 9.77 ppm (12.2 ppm, ± 1σ) and 6.71 ppm (8.28 ppm, ± 1σ), respectively. PCB concentrations exponentially wane away from the riverbank within oxbow and floodplain deposits of both the shallow and deeper subsurface.

Oxbows contain the greatest concentrations of PCBs, but their paucity means that the surrounding floodplain is the largest sink for PCB-laden sediment (Fig. 4C). PCB storage is significantly greater in the surrounding floodplain than in oxbows (t-test: $\alpha < 0.01$; Mann-Whitney: $\alpha < 0.01$) and averages 1170 kg (1230 kg, ± 1σ) and 303 kg (732 kg, ± 1σ), respectively. Similar to PCB concentrations, PCB storage exponentially wanes from the riverbank within both alluvial settings. The pattern may reflect the exponential decline in suspended sediment loading away from the riverbank as is documented in field observations of floodplain deposits and formulated in theoretical expressions of floodplain sedimentation (Magilligan, 1992; Lauer and Parker, 2008; Pizzuto et al., 2008; Pizzuto et al., 2016). Summing across all bins provides an estimate of the total storage of each alluvial setting. Our estimates indicate that the surrounding floodplain (total surface area 5.83 km^2 without oxbows) is storing as much as 14.1 t of PCBs, which is equivalent to 2.42 g m^{-2} of PCBs. Although oxbows represent only 5.26% of the 6.15 km^2 floodplain, they are storing as much as 3.63 t, or more than 21%, of all PCBs, equivalent to 11.2 g m^{-2}. Nearly 85% of oxbow storage of PCBs occurs within the first 50 m of floodplain, reflecting processes of fine-grained sediment loading and the prevalence of recently created oxbows. Although river meandering could remobilize these deposits over centennial timescales, microbial degradation may sufficiently reduce concentrations within this timeframe (Borja et al., 2005; Needham et al., 2019). If river management prevents oxbow production, alluviation will gradually reduce the availability of critical floodplain sinks for sediment-associated pollutants.

CONCLUSIONS

Oxbow lakes are critical sinks for pollutant-laden sediment in the floodplain of the Housatonic River. The storage efficiency of oxbows can be related to the characteristics of their deposits. Oxbows contain significantly higher fractions of both fine sediment and organic carbon than the surrounding floodplain, but PCB

[1]Supplemental Material. Radiometric data from Woods Pond, Massachusetts, loss-on-ignition data from cores collected along transect T1, and coordinates of core locations. Please visit https://doi.org/10.1130/GEOL.S.17052146 to access the supplemental material, and contact editing@geosociety.org with any questions.

concentrations appear to positively correlate only with fines. The importance of fine-grained sediment loading is supported by our coring data. In spite of significant spatial variability in PCB storage, average concentrations within oxbows are nearly twice that of the surrounding floodplain. And although the floodplain is the largest sink, oxbows disproportionately store the greatest loads of PCBs, nearly five times that of the surrounding floodplain.

ACKNOWLEDGMENTS

This study was supported by U.S. National Science Foundation grant EAR 2026789 and the Department of Geosciences of Williams College (Massachusetts, USA). We thank Brad Wakoff and Harry Desmond for assistance in the coring expedition; David P. Richardson and Mia Holtz for pioneering PCB work; and Xiaoyi Zhang and Ziyang Shen for assistance in grain-size calculations. We also thank the Western Region of Massachusetts Department of Fish and Game for permission to access the floodplain for our coring survey, and Kelsey Dumville of EPA New England (Region 1) for providing the archival data. We are grateful for the thoughtful reviews of James Pizzuto and Samuel Muñoz that improved the manuscript.

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