EPA Public Access

Author manuscript

Integr Environ Assess Manag. Author manuscript; available in PMC 2018 August 13.

About author manuscripts

Submit a manuscript

Published in final edited form as:

Integr Environ Assess Manag. 2017 July ; 13(4): 675–685. doi:10.1002/ieam.1844.

Particle bound metal transport following removal of a small dam in the Pawtuxet River, Rhode Island, USA

David R. Katz^{†,*}, Mark G. Cantwell[†], Julia C. Sullivan[‡], Monique M. Perron[§], Robert M. Burgess[†], and Kay T. Ho[†]

[†]US Environmental Protection Agency, Office of Research and Development (ORD), National Health and Environmental Effects Research Laboratory (NHEERL), Atlantic Ecology Division (AED), 27 Tarzwell Drive, Narragansett, RI 02882, (401)-782-3000

[‡]Oak Ridge Institute for Science and Education, Narragansett, RI 02882 USA

[§]U.S. Environmental Protection Agency, Office of Pesticide Programs, Washington, DC 20460 USA

Abstract

The Pawtuxet River in Rhode Island, USA has a long history of industrial activity and pollutant discharges. Metal contamination of the river sediments are well documented and historically exceeded toxicity thresholds for a variety of organisms. The Pawtuxet River dam, a low-head dam at the mouth of the river, was removed in August 2011. The removal of the dam was part of an effort to restore the riverine ecosystem after centuries of anthropogenic impact. Sediment traps were deployed below the dam to assess changes in metal concentrations and fluxes (Ag, Cd, Cr, Cu, Ni, Pb, & Zn) from the river system into Pawtuxet Cove. Sediment traps were deployed for an average duration of 24 days each, and deployments continued for 15 months after the dam was removed. Metal concentrations in the trapped suspended particulate matter (SPM) dropped following dam removal (e.g. 460 mg/kg to 276 mg/kg for Zn) and remained below pre-removal levels for most of the study. However, particle bound metal fluxes rose immediately following dam removal (e.g. 1206 g/d to 4248 g/d for Zn). Changes in flux rates during the study period indicated that river volumetric flow rates acted as the primary mechanism controlling the flux of metals into Pawtuxet Cove and ultimately upper Narragansett Bay. While SPM metal concentrations initially dropped after removal of the dam, no discernable effect on the concentration or flux of the study metals exiting the river could be associated with removal of the Pawtuxet River dam.

Keywords

metal flux; particle bound metals; dam removal; sediment traps

*To whom correspondence may be addressed.

Contact information: katz.david@epa.gov, cantwell.mark@epa.gov, sullivan.julia@epa.gov, perron.monique@epa.gov, burgess.robert@epa.gov, ho.kay@epa.gov

INTRODUCTION

Metals are released to the aquatic environment through numerous anthropogenic activities and natural processes. Metal toxicity in aquatic systems is dependent on metal speciation, with dissolved phase metals more bioavailable and potentially posing a greater toxicity and bioaccumulation risk than those in the particulate phase (Cantwell et al. 2002; USEPA 2005). Remobilization and transport of sediment-bound metals from contaminated areas poses a risk to downstream locations, particularly to where metal concentrations were previously not a concern. Upon resuspension by physical disturbance via anthropogenic or natural forces, such as storms, dredging or dam removal activities, transport of particulate bound metal contaminants may be enhanced.

Dams are installed for a range of purposes (e.g., power generation, flood control, navigation, water supply); however, many existing dams no longer perform the function for which they were designed or are structurally unsound (Whitelaw and Macmullan 2002). Additionally, benefits of dams are often outweighed by the cost in ecological impairment due to changes in sediment transport, nutrient transport, temperature, river hydrology and geomorphology, and biological diversity and mobility (Baish et al. 2002; Bednarek 2001; Graf 1999; Gregory et al. 2002; Hart et al. 2002; Poff and Hart 2002; Stanley and Doyle 2002). Due to these factors and the additional economic costs of maintenance and potential liability (Bowman 2002; Gregory et al. 2002), public awareness and support has increased for many dam removal projects, with many targeted for removal recently (Nijhuis 2015). Research into post-removal sediment erosion, transport, and subsequent redeposition are among the most important concerns facing future dam removal projects (Graf 2002; Stanley and Doyle 2003). The transport of sediment-bound contaminants are only recently being addressed in the literature (Csiki and Rhoads 2014; Pearson and Pizzuto 2015); and studies have shown the potential for downstream contamination (Ashley et al. 2006; Cantwell et al. 2014; Evans and Gottgens 2007; Peck et al. 2007; Sando and Lambing 2011). While over 500 dams have been removed in the past decade, the few studies related to dam removal have been of short duration, opportunistic and of limited scope (O'Connor et al. 2015).

The U.S. Army Corps of Engineers maintains a National Inventory of Dams with over 87,000 dams within the U.S., of which 49% are below 25 ft in height and 3.4% were constructed prior to 1900 (USACE 2015). This database includes only high hazard dams or dams above 6 ft in height. The U.S. Soil Conservation Service estimated that since 1900, the service had assisted in the construction of approximately 2.5 million low head dams (Buie 1979) and other research puts the number of existing low head dams at approximately 2 million (Graf 1993). Current, precise information on the total number of dams throughout the U.S. is not known. In Rhode Island, dam safety inspections are conducted yearly and 667 have been identified, of which at least 20 % were constructed prior to 1900 and 57 % are low-head dams (RIDEM 2015a).

The Pawtuxet River (Figure 1) is located in central Rhode Island and its headwaters originate from the Scituate Reservoir. The river has an associated watershed with an area of 611 km² (Ziegler and Nisbet 1994) before discharging to Pawtuxet Cove, a natural harbor within upper Narragansett Bay about 20 km downstream of the Scituate Reservoir. Over the

last 70 years the Pawtuxet River has had an average flow of 10 m³/s (USGS 2015). Historically, industrial activities have utilized the Pawtuxet River for many purposes. The river was first impounded during the colonial period when the need for grist and saw mills led to the construction of dams for hydropower. From the U.S. Industrial Revolution until implementation of the Clean Water Act of 1972, mills along the riverbanks discharged industrial wastes directly to the river. Metal contamination of the Pawtuxet began around 1840–1850 (Corbin 1989). In the 1930s, manufacturers of precious metals, jewelry, auto parts and chemicals were active along the river (Latimer et al. 1988). Environmental regulations have significantly reduced the release of contemporary contaminants to the Pawtuxet River. However, the cumulative history of industrial activity within the river watershed has left a legacy of contamination within the riverine system (water, sediment and biota), Pawtuxet Cove and extending out into Narragansett Bay (Corbin 1989; Lopez-Avila and Hites 1980; Nixon 1995; Seavey and Pratt 1979). These legacy contaminants include the metals cadmium, chromium, copper, lead, zinc, silver and nickel—all of which have been present in concentrations toxic to aquatic life at levels above consensus based freshwater sediment quality criteria (Burton 2002; MacDonald et al. 2000).

The Pawtuxet River dam was targeted by local stakeholders as well as state and federal government agencies for dam removal and subsequent ecological restoration of the river. This effort was undertaken to reestablish passage of anadromous fish and to restore biodiversity to the river. The dam removed from the mouth of the river was a weir-type structure approximately 1.7 m in height and 50 m in length (EA Engineering 2010). Removal of the dam was forecasted to lower the height of the interface between the Pawtuxet River and Pawtuxet Cove to 0.6 m, which is 1.1 m lower than pre-removal (EA Engineering 2010). The lower water level at the mouth of the river was predicted to have an effect on water levels as much as 8.4 km upriver, yet the effects were most significant in the 4.9 km upriver of the dam (EA Engineering 2010). The center streambed up to 90 m upriver of the dam is scoured and heavily armored with little organic matter present; however, the edges of the river contained between 0.5–1.5 m of sediment (Kleinschmidt 2005). The low dam height and little impounded sediment directly behind the dam eliminated direct remobilization of impounded sediments as a major concern. However, five of the known metal contaminants (Cd, Cu, Pb, Hg, and Zn) were found to exceed consensus sediment quality criteria at one or more sites above the dam during the initial feasibility study (Kleinschmidt 2005), and six (Cd, Cr, Cu, Pb, Hg and Zn) were reported to exceed those values at all sites sampled located just above the dam in the application for regulatory approval of the dam removal (EA Engineering 2010). Therefore, the potential for remobilization of contaminants archived in newly exposed Pawtuxet River bank sediments in the suspended sediment load as a result of dam removal was a concern and motivation for this study. This concern was due to the combination of the low dam height and the low vertical gradient traversed by the river, which causes the river backwater to extend up to 7.25 km upriver. The water levels were forecast to drop by 0.5 m up to 2.8 km upstream, which in turn increases channel shear stress and potentially exposes sediments to increased mobilization (EA Engineering 2010). Therefore, dam removal and lowering of river gage height could cause a migration of the knickpoint (*i.e.*, change in channel slope) upriver from

the dam and progressively remobilize archived upriver sediments over time in the suspended sediment load (Grant and Lewis 2015).

The objective of this research was to: a) estimate the magnitude of particulate metals exiting the river before and after the removal of the Pawtuxet River dam, and b) identify potential impacts from dam removal by examining relationships between metal concentrations and variables such as river flow and total suspended sediments. The concentrations and fluxes of metals exiting the river were determined by the deployment of sediment traps below the dam to assess the impact of dam removal on particle bound metal transport. A sediment core was also collected upstream of the sediment trap site in a depositional area in order to provide a temporal estimate of the concentrations of study metals (*i.e.* Ag, Cd, Cr, Cu, Ni, Pb, and Zn).

METHODS

Study site and field sampling

Gardner style cylindrical sediment traps with honeycomb baffles at the entrance (Cantwell et al. 2014; Gardner 1980) were deployed below the dam to collect suspended particulate matter (SPM) in Pawtuxet Cove (Figure 1). This site was located 50 m below the dam location in approximately 4 m of water. This site location was chosen to minimize the trap exposure to turbulence and mixing at high river flows nearer to the dam site. While this location is tidally influenced, salinity in this portion of the cove is generally very low but was measured during the study period by refractometer. Sediment traps were deployed continuously during the study period (July 28, 2011 – December 20, 2012). Preservatives were not added to the traps during or following deployment. Recovered SPM samples were stored at 4°C after retrieval and freeze dried (VirTis Advantage 2.0, SP Scientific, Gardiner, NY) the same day as recovery whenever possible. A full discussion of SPM sample preparation is found in Cantwell et al. (2014).

Measured flows on the lower Pawtuxet River (USGS site 01116500) were averaged both daily and over each deployment period (USGS 2015). River flows were adjusted for ungaged river flow using a factor of 1.14 (Cantwell et al. 2014). This correction takes into account the contribution of additional watershed drainage and additional ungaged river flow contributed by the Pocasset River, which enters the Pawtuxet River flow down river from the USGS measurement location. SPM concentrations at the mouth of the Pawtuxet River below the dam were also collected periodically to determine typical suspended sediment concentrations under varying flow regimes. Salinity measurements at this location were also taken periodically.

Additionally, a sediment core was collected in 2007 from a location 0.7 km upriver from the dam location (Figure 1). Sediment core subsamples were treated in the same manner as SPM material collected in the sediment traps. A single sediment core may not be representative of the all bedded sediments, therefore previously reported sediment concentrations were also used for reference to guide interpretation of SPM metal results from the sediment traps (Ciba Specialty Chemicals Corporation 2003; EA Engineering 2010).

Sample digestion procedure

Sediment subsamples from each sediment trap (0.5 g) were sieved to $< 63 \mu\text{m}$, weighed in duplicate and placed in 15 mL polyethylene vials. Sediments were digested using concentrated trace metal grade acids (J.T. Baker, Center Valley, PA), nitric : hydrochloric : hydrofluoric acids at 3:2:1 mL/vial. Samples were allowed to stand for 20 min in the fume hood to digest organic matter, and were then sonicated three times for 1 h intervals (25 °C) with samples vortexed after each interval. Samples were then transferred to a hot block (DigiPREP Jr, SCP Science, Champlain, NY) and allowed to digest for 1 h (100 °C) before cooling overnight in a contained negative pressure environment. High purity water (Milli-Q Element, Millipore, Billerica, MA) was added to maintain volumes at approximately 6 mL. After cooling overnight, high purity water was added as needed to bring volumes to 10 mL. Digests were vortexed again and sonicated for 1 h at 25 °C. Digests were then centrifuged at 1500 rpm for 10 min, decanted into trace metal clean polyethylene volumetric flasks and diluted to 100 mL with high purity water. Each digest was then filtered through a Nuclepore® filter (GE Healthcare Life Sciences, Marlborough, MA) in a trace metal clean polycarbonate filtration apparatus. Samples were then stored in trace metal grade polyethylene sample bottles.

Instrumental methods

In addition to metal concentrations, sediments were characterized for grain size distribution and organic carbon content. After SPM homogenization, grain size was determined from representative bulk samples collected from each sediment trap deployment using a laser diffraction particle size analyzer (Mastersizer 2000, Malvern Instruments Inc., Westborough, MA). Representative samples were sieved to $<63 \mu\text{m}$, a portion of which was analyzed for organic carbon content (TOC) (Flash EA112, CE Elantech, Inc., Lakewood, NJ) before digestion of sieved sample material for metals analysis.

An Ultima2® (HORIBA Jobin Yvon, Edison, NJ) inductively coupled plasma – optical emission spectrometer (ICP-OES) was used to quantify metals within the digested samples. Standards were prepared from a primary stock solution (Ultra Scientific, North Kingstown, RI) in 5 % nitric acid and stored in polyethylene sample bottles (Nalgene, Rochester, NY) in the dark. The ICP-OES instrument was calibrated for each element using a 10 point standard curve ($R^2 = 0.995$) formulated from a National Institute for Standards and Technology (NIST) traceable standard. The instrument was set to scan across one wavelength for quantitation of each element, and blank subtracted maximum peak intensity values were used to calculate concentrations from the appropriate calibration curve. Concentrations (mg/L) as reported by the instrument were converted to mass concentrations based on the amount of material digested (mg/kg). Chemical analyses were conducted following rigorous quality control standards. All metals were analyzed utilizing blank and duplicate samples during each digestion in order to assess precision and accuracy. Duplicate samples were within 5% relative percent deviation while blanks were below detection limit. Standard reference materials (SRM) NIST 1944 (National Institute of Standards and Technology, Gaithersburg, MD) and MESS-3 (National research Council Canada, Ottawa, ON), an estuarine sediments with certified metal values, were digested and analyzed along with each

batch of SPM and sediment core samples. SRM recoveries for the metals in this study ranged between 80% and 115%.

Statistical analyses of the results using Pearson's product-moment correlation coefficient were computed using the Student's t-distribution ($p < 0.01$) within SigmaPlot 13 (Systat Software Inc, San Jose, CA).

Flux calculations

Metal fluxes during each sediment trap deployment were calculated using an empirical model of SPM concentration at the mouth of the river (Figure S1) developed during a prior study (Cantwell et al. 2014). This model calculated mean SPM during the deployment periods using flow rates from the mouth of the river and SPM collected from the trap location. Daily river flows were averaged to yield a mean river flow per deployment needed to calculate SPM fluxes (kg/d) and therefore metal fluxes by extension. Predicted average SPM concentrations in the river during each deployment from the model was used to generate average metal fluxes per deployment period by multiplying SPM fluxes with measured SPM metal concentrations (mg/kg) from sediment traps and adjusting for units. Information and data supporting this model is located in the supplemental information.

RESULTS AND DISCUSSION

Sediment trap deployments and river conditions

Deployment duration for each sediment trap averaged 24 days (ranging from 12 to 42 days). Average river flow during sediment trap deployments (Figure 2) was $10.6 \text{ m}^3/\text{s}$ and ranged between $3.2 \text{ m}^3/\text{s}$ and $28.9 \text{ m}^3/\text{s}$ per deployment (USGS 2015). During the study, daily average river flow ranged widely from 1.9 to $75.2 \text{ m}^3/\text{s}$, and averaged $11.8 \text{ m}^3/\text{s}$. The maximum daily average flow ($75 \text{ m}^3/\text{s}$) was observed during the December 2011 deployment, which coincided with a major wet weather event and was preceded by four deployments of above average flow. Using the SPM/river flow model described previously, approximately 5300 MT of suspended sediment was discharged from the river during the study (499 days). No clear effect on streamflow or gage height could be attributable to the removal of the dam during the study. Analysis of gage height variance over the course of the year prior to and following dam removal (*i.e.* 8/2010–8/2011 and 8/2011–8/2012) indicated a decrease of 12 cm (1.47 m before dam removal to 1.35 m the year after dam removal). This change is likely related to average river flow which was lower between years ($12.5 \text{ m}^3/\text{s}$ to $9.34 \text{ m}^3/\text{s}$) rather than changes due to dam removal, which is supported by the pre-removal forecast of negligible lowering of gage height at this location upriver (EA Engineering 2010). Rainfall amounts per year also were similar between years (115 cm to 123 cm) (NCEI). Measured salinities in the cove during the study period were low, generally 0.5 psu at a river flow of $14.1 \text{ m}^3/\text{s}$.

Particle-bound metals

There was only one deployment possible prior to dam removal and concentrations for all metals were generally higher before the dam removal than during the post-removal deployments. Concentrations of individual metals varied during the study (Figure 3 and

Table 1). Both Pb and Cu responded similarly over time, ranging from 35.1 to 186 mg/kg and 28.3 to 186 mg/kg, respectively (Figure 3a). Chromium had a minimum concentration of 28.4 mg/kg and also had the highest overall metal levels at 696 mg/kg (Figure 3a). Two metals, Ag and Cd (Figure 3b), both remained below 2.5 mg/kg for the study period, while Ni ranged from 6.6 to 37.7 mg/kg and Zn ranged from 86 to 460 mg/kg, respectively (Figure 3c). Both Cd and Zn were higher pre-removal throughout the study, while Ag, Ni, Pb and Cu had a single period in which post-removal concentrations were higher than pre-removal concentrations. The behavior of Cr was different from most other metals, with a large spike toward the end of the study which corresponded with a smaller increase in Ni during the same deployment. During the study, particle bound metal concentrations generally trended similarly between deployments. Average daily precipitation ranged from 0.06 cm to 0.78 cm per deployment with a median of 0.33 cm (Figure 3d). SPM collected in sediment traps ranged from 2.4% to 8.2% TOC with a median of 3.7% (Figure 3d) and was well correlated with river flow ($p < 0.01$). No seasonal trends were observed to affect metal concentrations during the study.

To determine the influence of river flow on the amount of particulate metal in the water column, metal concentrations were correlated with river flow using Pearson's product moment correlation coefficient (p). Significant correlation to river flow was observed for Ag, Cu, Ni, Pb, Zn and TOC ($p < 0.01$), whereas Cd and Cr showed a less significant relationship (Table 2). Correlation coefficients (r) for all the metals and TOC ranged from -0.375 to -0.707 , indicating that suspended particles became increasingly enriched in organic carbon as river flow declined. There was no significant relationship between river flow and percent sand ($r=0.11$, $p=0.61$) or percent silt ($r=0.13$, $p=0.55$). The percent silt and sand remained relatively uniform over a wide range of flows (Figure S2). We hypothesize that as river flow increased, sediment particles from elevated bank areas, which are less contaminated than the bedded sediments of the river, were entrained into the water column. Additionally, during wet weather conditions less contaminated particles from stormwater runoff that would be otherwise absent during dry conditions may contribute to particle loading in the river. Both factors were likely contributors to lower SPM metal concentrations during high flow volume periods which did not result in a significant increase in grain size.

Concentrations of all metals, however, showed a similar temporal trend throughout the study, indicating a shared source with the same factors controlling release of all metals analyzed. The Pawtuxet River bedded sediments, highly contaminated with metals from a long history of industrial activity, are considered the predominant source of particulate metals to the water column. SPM collected in Pawtuxet Cove did exceed consensus based estimates (Table S1) for freshwater sediments on several occasions (MacDonald et al. 2000). However, these values are not appropriate for evaluating ecological effects in this case.

Metal sources to the river

Analysis of the top 80 cm of the sediment core showed a sustained down-core increase in metal concentrations, indicative of long-term release and deposition to river sediments. Radiometric dating of this core was unsuccessful due likely to variable sediment sources, accumulation rates and possible disruption in the sediment record possibly due to one or

more high river flow events. However, documented PCB and PAH trends in the river provide an approximate sediment accumulation rate at several depths ranging between 1.7 and 2.5 cm/yr (Figure S3). This would indicate that declines in metal concentrations started occurring around the mid-1970s soon after implementation of the Clean Water Act. Further, this core did provide important information on the levels of contamination within the sediments and potentially available for resuspension.

Metal concentrations in the top 20 cm (Figure 4) were generally variable with large sub-surface peak concentrations at the 9–10 cm interval. The top 5 cm was very low in silt and high in sand when compared to the rest of the core, suggesting recent disturbance in the sediment record and is most likely related to a significant wet weather event. However, sediment grain size also changed abruptly at 19–20 cm, with % sand higher than % silt for the only interval below the top 5 cm of the core (Figure 4). TOC also dropped by almost half from 7% to 3.9% at the same core depth (Table 3). From 19–20 cm to 60 cm, metal concentrations for Ag, Cd, Cr, Cu, Pb, Zn, and to a lesser extent Ni, were variable, with peaks in concentration at 34–35 cm in all core profiles. All metal contaminants had peak concentrations near the base of the core, which indicates that overall loading of contaminants to the river has declined over time.

The range of SPM metal concentrations trapped from the water column (Figure 3) agrees well with levels measured in the upper 10 cm section of the core. The sediments at this interval are the most prone to resuspension due to physical disturbances caused by either dam removal or high flow conditions (*e.g.* large magnitude wet weather events). The data from this core provides evidence that resuspended sediments are the primary source of particulate metals to the water column of the Pawtuxet River and are eventually transported to Narragansett Bay. This line of evidence is further enhanced by sediment surveys conducted prior to removal, which showed similar levels of metal contamination in many locations throughout the river in the top 10 cm of sediment (Ciba Specialty Chemicals Corporation 2003; EA Engineering 2010).

Metal fluxes to Pawtuxet Cove

During the study, the wide range in daily average river flows had a major impact on calculated flux rates, with fluxes increasing with river flow. Overall, metal flux increased with flow despite decreased metal concentrations of the SPM as discussed previously. Prior to dam removal, fluxes were low for all metals. Following the dam removal, fluxes increased by approximately a factor of two for all metals as the river flow increased during the 5 subsequent trap deployments (Table 3). The highest calculated fluxes occurred during the 12/19/11 period for all metals, concurrent with the highest flow rates during the study (Figure 5). Following this high flow event, metal fluxes decreased as river flow rates declined during later deployments.

The average fluxes of each metal for all deployments were calculated, resulting in annual fluxes discharged to Narragansett Bay. The highest metal fluxes were for Zn (746 kg/y), Cr (301 kg/y), Pb (295 kg/y), and Cu (279 kg/y). Fluxes for Cd and Ag were considerably lower, with total fluxes of 4.1 kg/y and 3.5 kg/y, respectively (Table 3).

Overall, the calculated fluxes provide an estimate of the amount of metals exiting the river and entering Narragansett Bay. While these fluxes were particle-bound metals and may not have been bio-available, speciation and phase distribution can change over short time periods, particularly under dynamic estuarine conditions (Atkinson et al. 2007; Cantwell et al. 2002; Di Toro et al. 2005). This may result in the release of dissolved metals from suspended or redeposited material potentially increasing the exposure risk.

CONCLUSIONS

During this study, periodic fluctuations in metal fluxes were most closely attributable to river flow volume, although both increased SPM loading of the water column and dilution of metal-contaminated SPM by uncontaminated sediments were factors. A sediment core taken upriver found that upper core metal concentrations and previously reported data agreed well with observed metal SPM concentrations in sediment traps downriver. No discernable effects (*i.e.* large scale increases in metal concentrations) of dam removal were observable in the metal concentrations or fluxes over the study period. This was due in part to the low volume of sediment trapped behind the dam (Kleinschmidt 2005), but the single trap deployment prior to dam removal limited a longer term assessment of variability associated with metal fluxes. While dam removal did not show significant direct effects on metal fluxes out of the Pawtuxet River, bedded sediments continue to be a source of downstream contamination as indicated by the record of contamination within the sediment core and other surficial sediments. Consequently, discharge of significant amounts of metals to Pawtuxet Cove and upper Narragansett Bay will likely continue for the foreseeable future. Although the river is classified as impaired by the Rhode Island Department of Environmental Management under section 303(d) of the Clean Water Act due to lead, cadmium, and mercury contamination; regulations for allowable total maximum daily loads (TMDL) for these pollutants are not scheduled for completion until at least 2026 (RIDEM 2015b). This raises additional questions about appropriate regulatory approaches when confronted with contaminant loading to rivers when the rivers sediments are themselves the source of contamination due a legacy of pollution.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

The authors thank Walter Berry, Sandra Robinson and Jonathan Serbst for their technical reviews. Although research described in this article has been wholly funded by the U.S. Environmental Protection Agency and has been technically reviewed at the Atlantic Ecology Division, it has not been subjected to Agency-level review. Therefore, it does not necessarily reflect the views of the Agency. This manuscript is contribution number ORD-014496 of the Atlantic Ecology Division of the United States Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory. Mention of trade names does not constitute endorsement or recommendation for use.

REFERENCES

- Ashley JTF , Bushaw-Newton K , Wilhelm M , Boettner A , Drames G , Velinsky DJ . 2006 The Effects of Small Dam Removal on the Distribution of Sedimentary Contaminants. *Environ Monit Assess.* 114(1):287–312.16565804
- Atkinson CA , Jolley DF , Simpson SL . 2007 Effect of overlying water pH, dissolved oxygen, salinity and sediment disturbances on metal release and sequestration from metal contaminated marine sediments. *Chemosphere.* 69(9):1428–1437.17568653
- Baish SK , David SD , Graf WL . 2002 The Complex Decisionmaking Process for Removing Dams. *Environment: Science and Policy for Sustainable Development.* 44(4):20–31.
- Bednarek TA . 2001 Undamming Rivers: A Review of the Ecological Impacts of Dam Removal. *Environmental Management.* 27(6):803–814.11393315
- Bowman MB . 2002 Legal Perspectives on Dam Removal: This article outlines the legal issues associated with dam removal and examines how environmental restoration activities such as dam removal fit into the existing US legal system. *BioScience.* 52(8):739–747.
- Buie EC . 1979 A History of the United States Department of Agriculture Water Resource Activities. Philadelphia, PA: U.S. Government Printing Office No. 628–311/2592.
- Burton GA . 2002 Sediment quality criteria in use around the world. *Limnology.* 3(2):65–76.
- Cantwell MG , Burgess RM , Kester DR . 2002 Release and phase partitioning of metals from anoxic estuarine sediments during periods of simulated resuspension. *Environ Sci Technol.* 36(24):5328–5334.12521157
- Cantwell MG , Perron MM , Sullivan JC , Katz DR , Burgess RM , King J . 2014 Assessing organic contaminant fluxes from contaminated sediments following dam removal in an urbanized river. *Environ Monit Assess.* 186(8):4841–4855.24729181
- Ciba Specialty Chemicals Corporation. 2003 Sediment Sampling Report for the Pawtuxet River: Former Ciba-Geigy Facility, Cranston, Rhode Island. Wayne, New Jersey: Woodward-Clyde.
- Corbin JM . 1989 Recent and historical accumulation of trace metal contaminants in the sediment of Narragansett Bay, Rhode Island University of Rhode Island.
- Csiki SJC , Rhoads BL . 2014 Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology.* 206:215–229.
- Di Toro DM , McGrath JA , Hansen DJ , Berry WJ , Paquin PR , Mathew R , Wu KB , Santore RC . 2005 Predicting sediment metal toxicity using a sediment biotic ligand model: methodology and initial application. *Environmental Toxicology and Chemistry.* 24(10):2410–2427.16268143
- Engineering EA . 2010 Pawtuxet River Restoration Project Pawtuxet River, Cranston and Warwick, Rhode Island Application to Alter Warwick, RI No. EA Project No. 62277.01.
- Evans JE , Gottgens JF . 2007 Contaminant Stratigraphy of the Ballville Reservoir, Sandusky River, NW Ohio: Implications for Dam Removal. *Journal of Great Lakes Research.* 33(sp2):182–193.
- Gardner WD . 1980 Field assessment of sediment traps. *Journal of Marine Research.* 38(1).
- Graf WL . 1993 Landscapes, Commodities, and Ecosystems: The Relationship Between Policy and Science for American Rivers In: Water Science and Technology Board NRC, editor. *Sustaining our Water Resources.* Washington, D.C.: National Academy Press p. 11–42.
- Graf WL . 1999 Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research.* 35(4):1305–1311.
- Graf WL , editor. 2002 Dam Removal Research: Status and Prospects. *Proceedings of The Heinz Center's Dam Removal Research Workshop*; Washington, D.C. Washington, D.C.
- Grant GE , Lewis SL . 2015 The Remains of the Dam: What Have We Learned from 15 Years of US Dam Removals? In: Lollino G , Arattano M , Rinaldi M , Giustolisi O , Marechal J-C , Grant EG , editors. *Engineering Geology for Society and Territory - Volume 3: River Basins, Reservoir Sedimentation and Water Resources.* Cham: Springer International Publishing p. 31–35.
- Gregory S , Li H , Li J . 2002 The Conceptual Basis for Ecological Responses to Dam Removal: Resource managers face enormous challenges in assessing the consequences of removing large dams from rivers and evaluating management options. *BioScience.* 52(8):713–723.

- Hart DD , Johnson TE , Bushaw-Newton KL , Horwitz RJ , Bednarek AT , Charles DF , Kreeger DA , Velinsky DJ . 2002 Dam Removal: Challenges and Opportunities for Ecological Research and River Restoration: We develop a risk assessment framework for understanding how potential responses to dam removal vary with dam and watershed characteristics, which can lead to more effective use of this restoration method. *BioScience*. 52(8):669–682.
- Kleinschmidt. 2005 Pawtuxet River Authority and Watershed Council: Pawtuxet River Anadromous Fish Passage Restoration Project Feasibility Study.
- Latimer JS , Carey CG , Hoffman EJ , Quinn JG . 1988 Water-Quality in the Pawtuxet River - Metal Monitoring and Geochemistry. *Water Resour Bull*. 24(4):791–800.
- Lopez-Avila V , Hites RA . 1980 Organic compounds in an industrial wastewater. Their transport into sediments. *Environmental Science & Technology*. 14(11):1382–1390.
- MacDonald DD , Ingersoll GC , Berger AT . 2000 Development and Evaluation of Consensus-Based Sediment Quality Guidelines for Freshwater Ecosystems. *Archives of Environmental Contamination and Toxicology*. 39(1):20–31.10790498
- NCEI. Quality Controlled Local Climatological Data. National Centers for Environmental Information (NCEI) - National Oceanic and Atmospheric Administration 8, 2015 <https://data.noaa.gov/dataset/quality-controlled-local-climatological-data-qclcd-publication>.
- Nijhuis M 2015 Movement to Take Down Thousands of Dams Goes Mainstream. [accessed 2015 December]. <http://news.nationalgeographic.com/news/2015/01/150127-white-clay-creek-dam-removal-river-water-environment/>.
- Nixon SW . 1995 Metal Inputs to Narragansett Bay: A History and Assessment of Recent Conditions. Narragansett, RI
- O'Connor JE , Duda JJ , Grant GE . 2015 1000 dams down and counting. *Science*. 348(6234):496–497.25931537
- Pearson AJ , Pizzuto J . 2015 Bedload transport over run-of-river dams, Delaware, U.S.A. *Geomorphology*. 248:382–395.
- Peck JA , Mullen A , Moore A , Rumschlag JH . 2007 The Legacy Sediment Record within the Munroe Falls Dam Pool, Cuyahoga River, Summit County, Ohio. *Journal of Great Lakes Research*. 33:127–141.
- Poff NL , Hart DD . 2002 How Dams Vary and Why It Matters for the Emerging Science of Dam Removal: An ecological classification of dams is needed to characterize how the tremendous variation in the size, operational mode, age, and number of dams in a river basin influences the potential for restoring regulated rivers via dam removal. *BioScience*. 52(8):659–668.
- RIDEM. 2015a Annual Report to the Governor on the Dam Safety Program Providence, RI: Rhode Island Department of Environmental Management (RIDEM) - Office of Compliance and Inspection.
- RIDEM. 2015b State of Rhode Island 2014 303(d) List of Impaired Waters Providence, RI: Rhode Island Department of Environmental Management (RIDEM) - Office of Water Resources.
- RIGIS. 2011 2011 RIDEM Digital True Color Orthophotography. Rhode Island Geographic Information System (RIGIS) Data Distribution System. Environmental Data Center, University of Rhode Island, Kingston, Rhode Island; [accessed 2013 March]. <http://www.rigis.org>.
- Sando SK , Lambing JH . 2011 Estimated loads of suspended sediment and selected trace elements transported through the Clark Fork basin, Montana, in selected periods before and after the breach of Milltown Dam (water years 1985–2009): U.S. Geological Survey Scientific Investigations Report 2011–5030.
- Seavey GL , Pratt SD . 1979 The disposal of dredged material in Rhode Island : an evaluation of past practices and future options. Kingston: Coastal Resources Center, University of Rhode Island.
- Stanley EH , Doyle MW . 2002 A Geomorphic Perspective on Nutrient Retention Following Dam Removal: Geomorphic models provide a means of predicting ecosystem responses to dam removal. *BioScience*. 52(8):693–701.
- Stanley EH , Doyle MW . 2003 Trading off: the ecological effects of dam removal. *Frontiers in Ecology and the Environment*. 1(1):15–22.
- USACE. 2015 US Army Corps of Engineers (USACE) - National Inventory of Dams. [accessed 2015 December]. <http://www.nid.usace.army.mil>.

- USEPA. 2005 Procedures for the Derivation of Equilibrium Partitioning Sediment Benchmarks (ESBs) for the Protection of Benthic Organisms: Metal Mixtures. EPA-600-R-02-011. United States Environmental Protection Agency (USEPA) Office of Research and Development Washington, DC.
- USGS. 2015 USGS Water Data for USA. National Water Information System - United States Geological Survey (USGS); [accessed 2015 March]. http://waterdata.usgs.gov/nwis/uv?site_no=01116500.
- Whitelaw E , Macmullan E . 2002 A Framework for Estimating the Costs and Benefits of Dam Removal: Sound cost–benefit analyses of removing dams account for subsidies and externalities, for both the short and long run, and place the estimated costs and benefits in the appropriate economic context. *BioScience*. 52(8):724–730.
- Ziegler CK , Nisbet B . 1994 Fine-Grained Sediment Transport in Pawtuxet River, Rhode Island. *Journal of Hydraulic Engineering*. 120(5):561–576.

Figure 1.
Pawtuxet River study site (RIGIS 2011). Sediment trap site location shown as black circle.
Dam location shown as black bar. Core site shown as black triangle.

Figure 2.
Daily average river flow. Open circles represent average flow per sediment trap deployment.
Vertical gray bar indicates initiation date of dam removal work.

Figure 3.

Site 3 sediment trap concentrations during the study period. A) Cr, Cu, & Pb concentrations (mg/kg); B) Ag & Cd concentrations (mg/kg); C) Zn & Ni concentrations (mg/kg); D) %TOC & Avg Daily Precipitation (cm)

Figure 4. Core profiles of A) Ag and Cd; B) Cu, Pb, and Ni; C) Cr and Zn (all values mg/kg); and D) percent sand, silt, and clay

Figure 5. SPM Metal Fluxes per deployment (g/d) shown as stacked bars. Average river flow is shown by the black line. Dam removal began the same day the first sediment trap was recovered.

Table 1.

Metal concentrations in SPM collected in sediment traps. Shaded row indicates concentrations prior to dam removal.

Recovery Date	Ag (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	% TOC
09-Aug-11	1.96	2.42	149.82	177.35	30.86	172.58	460.27	8.18
12-Sep-11	0.85	1.49	96.25	81.65	20.53	103.41	276.51	3.69
11-Oct-11	0.61	1.03	66.01	61.99	14.20	75.02	193.86	2.90
01-Nov-11	0.57	0.50	28.36	28.29	6.57	35.11	89.50	2.51
29-Nov-11	1.02	1.33	75.61	80.80	15.93	92.15	232.77	3.84
19-Dec-11	0.97	1.12	87.23	68.47	16.21	75.69	192.62	2.50
10-Jan-12	0.76	0.45	62.10	38.01	15.56	36.34	86.34	2.67
31-Jan-12	0.62	0.89	53.30	72.55	11.68	64.40	159.83	2.39
28-Feb-12	1.21	1.28	69.13	108.63	13.15	87.50	210.77	3.72
13-Mar-12	1.23	1.25	86.51	115.80	16.93	91.14	231.23	3.28
04-Apr-12	1.35	1.10	60.97	95.57	14.25	77.84	190.82	3.40
24-Apr-12	0.67	1.02	74.83	69.81	16.59	82.26	213.03	3.74
23-May-12	0.73	1.08	73.02	76.58	15.13	80.16	212.18	2.93
12-Jun-12	0.99	1.41	96.61	101.58	18.41	107.23	279.24	4.94
10-Jul-12	1.15	1.12	93.10	102.94	17.30	102.35	257.36	4.58
24-Jul-12	1.75	1.20	118.54	153.01	19.34	129.39	271.28	5.45
28-Aug-12	1.45	0.99	196.00	145.73	23.47	122.87	272.54	4.58
25-Sep-12	1.60	1.38	696.22	169.20	37.77	147.70	338.03	5.77
06-Nov-12	1.91	1.47	132.09	172.62	20.96	140.87	361.46	5.37
04-Dec-12	2.16	1.43	131.35	185.90	21.39	140.41	299.94	5.41
20-Dec-12	1.86	2.13	152.18	168.94	24.33	186.50	418.54	4.60
Minimum	0.57	0.45	28.36	28.29	6.57	35.11	86.34	2.39
Maximum	2.16	2.42	696.22	185.90	37.77	186.50	460.27	8.18
Average	1.21	1.24	123.77	108.35	18.60	102.43	249.91	4.12

Table 2.

Pearson's product moment correlation (r-value) of SPM metal concentrations to river flow (m³/s)

	r-value	P-value
Ag	-0.602	0.00390
Cd	-0.416	0.06040
Cr	-0.375	0.09410
Cu	-0.707	0.00034
Ni	-0.569	0.00710
Pb	-0.639	0.00183
Zn	-0.602	0.00386
TOC	-0.638	0.00187

Table 3.

Metal flux to Pawtuxet Cove per deployment. Shaded row indicates concentrations prior to dam removal.

Recovery Date	Ag (g/d)	Cd (g/d)	Cr (g/d)	Cu (g/d)	Ni (g/d)	Pb (g/d)	Zn (g/d)	C (kg C/d)
09-Aug-11	5.13	6.33	392.82	465.03	80.93	452.52	1206.84	214.43
12-Sep-11	13.12	22.93	1478.87	1254.55	315.44	1588.95	4248.53	566.61
11-Oct-11	7.15	12.04	775.03	727.84	166.76	880.75	2276.09	340.47
01-Nov-11	19.69	17.21	983.32	981.01	227.79	1217.55	3103.34	869.55
29-Nov-11	28.12	36.63	2089.95	2233.38	440.27	2547.18	6434.28	1062.37
19-Dec-11	57.55	66.43	5162.11	4051.74	959.35	4479.05	11398.88	1482.37
10-Jan-12	11.24	6.71	922.30	564.51	231.09	539.67	1282.28	396.27
31-Jan-12	10.02	14.42	865.69	1178.42	189.74	1046.00	2595.92	388.84
28-Feb-12	7.09	7.45	403.36	633.80	76.75	510.54	1229.72	216.76
13-Mar-12	7.11	7.26	501.76	671.63	98.18	528.58	1341.08	190.01
04-Apr-12	2.93	2.39	132.55	207.76	30.97	169.22	414.83	73.84
24-Apr-12	2.05	3.16	230.49	215.03	51.09	253.37	656.19	115.29
23-May-12	5.94	8.79	597.12	626.26	123.76	655.53	1735.15	239.27
12-Jun-12	4.19	6.01	410.47	431.58	78.21	455.59	1186.40	209.97
10-Jul-12	2.78	2.72	225.61	249.44	41.93	248.02	623.63	110.94
24-Jul-12	1.10	0.76	74.46	96.12	12.15	81.28	170.41	34.23
28-Aug-12	1.36	0.93	184.06	136.85	22.04	115.39	255.93	43.04
25-Sep-12	2.41	2.08	1048.19	254.74	56.87	222.37	508.91	86.83
06-Nov-12	4.70	3.62	324.85	424.53	51.55	346.46	888.96	132.09
04-Dec-12	3.56	2.36	216.90	306.99	35.33	231.88	495.32	89.31
20-Dec-12	3.88	4.45	318.49	353.57	50.92	390.32	875.96	96.18
Minimum	1.10	0.76	74.46	96.12	12.15	81.28	170.41	34.23
Maximum	57.55	66.43	5162.11	4051.74	959.35	4479.05	11398.88	1482.37
Average	9.58	11.17	825.64	764.99	159.10	807.63	2044.22	331.37
Yearly Average (kg/y)	3.50	4.08	301.36	279.22	58.07	294.79	746.14	120.95