Environmental Dredging Residual Generation and Management

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ABSTRACT

The presence and magnitude of sediment contamination remaining in a completed dredge area can often dictate the success of an environmental dredging project. The need to better understand and manage this remaining contamination, referred to as “postdredging residuals,” has increasingly been recognized by practitioners and investigators. Based on recent dredging projects with robust characterization programs, it is now understood that the residual contamination layer in the postdredging sediment comprises a mixture of contaminated sediments that originate from throughout the dredge cut. This mixture of contaminated sediments initially exhibits fluid mud properties that can contribute to sediment transport and contamination risk outside of the dredge area. This article reviews robust dredging residual evaluations recently performed in the United States and Canada, including the Hudson River, Lower Fox River, Ashtabula River, and Esquimalt Harbour, along with other projects. These data better inform the understanding of residuals generation, leading to improved models of dredging residual formation to inform remedy evaluation, selection, design, and implementation. Data from these projects confirm that the magnitude of dredging residuals is largely determined by site conditions, primarily in situ sediment fluidity or liquidity as measured by dry bulk density. While the generation of dredging residuals cannot be avoided, residuals can be successfully and efficiently managed through careful development and implementation of site-specific management plans.

INTRODUCTION

Contaminated sediments pose unique challenges, both technically and administratively. Throughout North America, governmental agencies and responsible parties have been investigating, evaluating, and remediating contaminated sites since the early 1980s under a range of regulatory frameworks; environmental dredging has most often been the remedial technology employed (Doody et al. 2013). Although the objective of environmental dredging is to reduce potential risks to human health and the environment, unfortunately it is still not clear whether environmental dredging alone effectively reduces such risks (Wenning et al. 2006; NRC 2007; Gustavson et al. 2008; Bridges et al. 2010). Even today, the scientific community seeks effective approaches to manage contaminated sediment risks.

Experiences throughout North America have shown that environmental dredging can be very expensive, with a large portion of the total cost attributable to the management and disposal of the sediment removed (Doody et al. 2013). The combined cost to remediate two of the largest sediment cleanup sites in North America—the Hudson River (NY, USA) and the Lower Fox River (WI, USA)—is approaching US$3 billion, with other large sites still on the horizon. These high costs, coupled with uncertain risk reduction outcomes, have led many practitioners to redouble efforts to collect, learn from, and incorporate new information to improve the effectiveness of remedial operations (Bridges and Patmont 2011).

Over the past 30 years, more than 100 environmental dredging projects were completed throughout North America (Doody et al. 2013). As discussed in National Research Council (NRC 2007), Gustavson et al. (2008), and Bridges et al. (2010), surface sediments remaining after these environmental dredging operations still contained elevated contamination levels. These contaminated sediments, referred to as “postdredging residuals” (Figure 1), likely occurred due to 2 primary factors: 1) limitations of even
the most effective dredging equipment (discussed in the FORMATION OF GENERATED RESIDUALS section) and 2) variable distribution of contamination found in many sites (including relatively high contaminant concentrations at depth below the sediment surface from legacy releases).

Chemical monitoring before, during, and after environmental dredging projects has documented contaminant release into the water column (also referred to as “resuspension”) as well as newly exposed postdredging residuals, increasing exposure and risk to biota (Bridges et al. 2010). Although contaminant releases into the water column often cease upon completion of dredging operations, postdredging residuals can lead to persistent exposure and risk to biota (Bridges et al. 2010). Laboratory studies have shown that contaminant fluxes into the overlying water column vary among undisturbed sediments, roughened sediments, and generated residuals (Karim et al. 2014).

The bioavailability of postdredging residuals may be different from predredging sediments (Alexander 2000; Reid et al. 2000). Some postdredging residuals, especially those classified as generated residuals (described further in this section), have higher fluidity, transport potential, and bioavailability, and thus are a particular exposure concern during environmental dredging (Heise and Ahlf 2002). Contaminated sediments remaining at the postdredging surface of the sediment profile, either within or adjacent to the dredging footprint, can be broadly grouped into 2 categories (Figure 1; see Bridges et al. 2010):

1) Undisturbed residuals: contaminated sediments that were not removed during dredging. Undisturbed residuals are usually the result of an underestimation of the depth of the initial dredge cut, often due to limited predredging characterization of the depth of contamination. Even with proper predredging characterization, undisturbed residuals can result from incomplete removal of the dredge prism line due to engineering limitations, presence of bedrock or hardpan, or physical structures such as bridges and piers that are inaccessible with dredging equipment.

2) Generated residuals: contaminated postdredging disturbed sediments that are dislodged or suspended by the...
dredging operation and subsequently redeposit on the bottom of the water body. As discussed further in this section, both mechanical and hydraulic dredging operations leave behind generated residuals due to resuspension, transport, and downstream deposition; dredge mixing and deposition; and sloughing or slumping (USACE 2008). Because of their relatively higher fluidity, generated residuals are prone to transport away from the point of dredging as fluid mud. The dredging equipment used on a site is governed by the contaminated sediment characteristics; production dredging equipment might not be well suited to removing low-density generated residuals.

Although robust site characterization can minimize undisturbed residuals and improve the overall cost-effectiveness of environmental dredging (Wasserman et al. 2013), the formation and quantification of generated residuals is less understood. Past studies have observed a relationship between the magnitude of generated residuals (expressed as a fraction of the contaminant mass dredged) and the density or liquidity of the dredged sediment (Patmont and Palermo 2007). However, previous estimates of generated residuals were based on empirical relationships developed using limited pre- and postdredging site characterization data.

Proper assessment and management of generated residuals requires robust pre- and postdredging sampling. Ideally, both pre- and postdredging sediment samples should be collected using a statistically robust sampling plan (e.g., sampling grid with irregularly spaced samples to represent areas that are not captured in the regular grid). Elevated postdredging subsurface sediment contamination concentrations are often representative of undisturbed residuals, whereas postdredging surface contamination can be a combination of generated and undisturbed residuals. Depending on the measured residual contamination levels and the fluidity or liquidity of the postdredging residuals, additional cleanup measures (e.g., clean sand cover placement) are often implemented to achieve risk reduction objectives. A representative generated residuals characterization and management schematic is shown in Figure 3.

**FORMATION OF GENERATED RESIDUALS**

Generated residuals are produced during both mechanical and hydraulic dredging operations (NRC 2007; Patmont and Palermo 2007; Gustavson et al. 2008). “Mechanical dredging” refers to the removal of sediments by mechanical excavation with buckets. During the mechanical dredging process, typical dredge buckets cut nearly vertical walls in the sediment. Once the bucket is raised out of the sediment, vertical sediment sidewalls surround the dredged area on sides that have not yet been dredged. These sidewalls are subject to sloughing failure as soon as they are formed, and failure is more likely with both deeper dredge cuts and in site-specific sediments with higher in situ fluidity or liquidity (Figure 1).

“Hydraulic dredging” refers to the removal of sediments through a suction tube powered by a pump and impeller. Hydraulic dredges typically have a cutterhead or other mechanical agitation device at the end of the suction line to facilitate sediment removal by loosening and blending sediment with surface water to form a fluid slurry that can be transported through the suction line. Hydraulic dredges are normally configured with the inlet of the suction pipe above the lowest reach of the rotating cutterhead; the mixed layer generated by the cutterhead is not fully removed by the suction pipe, leaving behind a “spillage layer” after dredging (Fuglevand and Webb 2012).

Tiwari and Hayes (2012) identified sidewall sloughing failure as a primary mechanism for generated residuals associated with mechanical dredging, with calculated generated residual losses ranging from approximately 1% to 15% of the dredge bucket volume, depending on the size of the bucket, depth of the cut, and the sediment sloughing and failure angle, which varies based on site-specific sediment characteristics. Additional generated residual mechanisms include sloughing from the lateral side opening during bucket closure and postclosure spillage from overfilling the bucket, a process that can be mitigated with enclosed buckets and best management practices (BMPs). Smaller buckets, tighter location controls, thinner dredge cuts (e.g., <1 m), a final cleanup dredge pass, and other operational BMPs can reduce residuals from mechanical dredging operations, but generated residuals cannot be eliminated (NRC 2007; Patmont and Palermo 2007; Gustavson et al. 2008).

Fuglevand and Webb (2012) reviewed hydraulic dredging equipment and operations, and summarized the “spillage” layer of mixed sediment that is generated as the cutterhead disturbs and mixes sediments to a depth greater than that recovered by the dredge suction pipe. The amount of spillage is a function of the relationship between the diameters of the cutterhead and discharge pipes. Fan et al. (2004) noted that different hydraulic dredging methodologies can affect the magnitude of water column releases and postdredging residuals. Mills and Kemps (2016) summarized how hydraulic dredging operating parameters can affect sediment resuspension. As summarized by Tiwari and Hayes (2012), sidewall sloughing failure also contributes to residual
generation from hydraulic dredging operations, which can be managed to some degree by using smaller diameter dredges, phased and/or controlled cuts, and other operational BMPs. Based on engineering and geotechnical considerations, as well as the case studies summarized subsequently, the overall magnitude of generated residuals is similar between mechanical and hydraulic dredging operations.

**PHYSICAL AND CHEMICAL CHARACTERISTICS OF GENERATED RESIDUALS**

As discussed in Patmont and Palermo (2007), generated residuals typically accumulate above the dredging cutline in thin layers of relatively less dense sediments compared to the targeted sediment within the dredge prism. Undisturbed residuals remain below the cutline as higher density (relative to generated residuals) sediment that may exist as either thin or thick layers, largely dependent on the robustness of the predesign site characterization. Sediment profile imaging, visual examination, and/or geotechnical testing have been used to differentiate generated residuals and determine their thickness.

Depending on thickness and geotechnical characteristics, disturbed fluidized sediments may persist for hours to days before re-forming as a generated residuals layer with in situ dry densities approaching those of fluid mud (Figure 4). During this initial consolidation period, fluidized sediments can be transported hundreds of meters from the dredging operation, depending on site-specific currents and other transport characteristics (Anchor Environmental 2006). Self-weight consolidation and compression settling tests indicate that generated residuals often remold to near predredging surficial densities within days to weeks, again depending on site-specific thickness and geotechnical characteristics (Cargill 1986).

In 2007, the US Environmental Protection Agency (USEPA) performed a detailed investigation of sediment residual formation during environmental hydraulic dredging operations on the Ashtabula River (OH, USA), with the goal of improving predictions of generated residual mass, volume, and chemical volume and chemical concentrations (USEPA 2010). Extensive monitoring studies and physical and chemical measurements were performed prior to, during, and after dredging. Multiple lines of evidence were used to evaluate residuals generated during dredging, including pre- and postdredging sediment core analyses, PCB fingerprinting, 2- and 3-dimensional PCB modeling, bathymetric surveys, and dredge cutterhead positioning. The evaluations revealed that the generated residual layer comprises sediments that originated from throughout the overlying dredge cut, rather than sediments removed from immediately above the final postdredging sediment surface (i.e., the last production cut). The average in situ dry density of generated residuals was approximately 20% lower than sediments in the dredge prism, and generated residual chemical concentrations were equivalent to the mass-weighted average over the entire dredge cut, consistent with findings from other recent case studies.

**GENERATED RESIDUALS MASS BALANCE CALCULATIONS**

Patmont and Palermo (2007) summarized initial mass balance calculations from a series of early environmental dredging case studies to develop initial “bounding-level” expectations of generated residuals for use in project planning. However, these earlier dredging projects did not employ statistically robust pre- or postdredging sediment characterization programs, and the resulting mass balance evaluations were thus variable and uncertain. Nevertheless, the resulting bounding-level estimates proved useful in guiding dredging residual management programs on subsequent environmental dredging projects.

Since 2007, improvements in environmental dredging data collection programs have resulted in the ability to refine generated residual mass balance calculations, supporting more rigorous and precise evaluations compared to earlier studies. These improvements include the following:

- Pre- and postdredging site characterization using statistically based robust sampling programs that reliably distinguished between generated and undisturbed residuals
- Use of the most effective environmental dredging equipment tailored to site conditions, along with controlled environmental dredging operations and rigorous BMPs.

In particular, 4 environmental dredging projects have recently been performed that employed highly robust pre- and postdredging sediment characterization programs: 1) Ashtabula River, 2) Lower Fox River, 3) Hudson River, and 4) Esquimalt Harbour (BC, Canada). These environmental dredging projects, which (except for the Hudson River) were performed in areas with relatively weak currents (typically less than 10 cm/s; Hudson River currents ranged up to 20 cm/s), are summarized as follows:

- Ashtabula River; USEPA (2010); https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=230173
- 11 000 m³ dredged in 2007

![Figure 4](image-url)
• 20-cm articulated cutterhead hydraulic dredge (other dredges were also used outside of the area investigated by USEPA for sediment residual formation)
• 30 pre- and postdredging core locations: 15- to 30-m grid spacing
• Lower Fox River; USEPA (2015); Fox River Group (2018); https://www.epa.gov/green-bay-fox-river-aoc; http://foxrivercleanup.com
• 2 900 000 m$^3$ dredged from 2009 to 2015 (projected 2019 completion)
• 20- and 30-cm articulated cutterhead hydraulic dredges
• 4300 pre- and postdredging core locations: 30- to 60-m grid spacing
• Hudson River; USEPA (2017); GE (2018); https://www3.epa.gov/hudson; http://www.hudsondredging.com
• 1 800 000 m$^3$ dredged from 2011 to 2015
• 4-m$^3$ enclosed clamshell mechanical dredges
• 8000 pre- and postdredging core locations: 25- to 50-m grid spacing
• Esquimalt Harbour; Canada Defence (2018); https://www.canada.ca/en/department-national-defence/news/2016/09/esquimalt-harbour-recapitalization-remediation-projects.html
• 150 000 m$^3$ dredged from 2013 to 2014
• 8-m$^3$ enclosed clamshell mechanical dredge
• 270 pre- and/or postdredging core locations: 20- to 40-m grid spacing

On all four of these robust dredge characterization projects, generated residuals were differentiated from undisturbed residuals based on visual observations and geotechnical measurements. As discussed in the FORMATION OF GENERATED RESIDUALS section, the calculated mass of contaminants remaining in the postdredging generated residual layer was compared to the mass of contaminants in the predredging prism, and expressed as an overall mass percentage for each dredging season.

Detailed generated residual PCB mass balance calculations for the Ashtabula River project are presented in USEPA (2010). For the Lower Fox River, Hudson River, and Esquimalt Harbour projects, the contaminant mass in the design prism was calculated based on the robust predesign sampling data. This predredging contaminant mass is denoted by $M_{\text{predredge}}$ in the subsequent equations.

Depending on the project, postdredging core segments used for the generated residual mass balance were collected over the top 10 to 15 cm; all generated residuals were assigned to this surficial sample depth interval (Figure 3). The contaminant mass in the generated residual layer was calculated based on similarly extensive postdredging sampling data, following verification (using bathymetric surveys and detailed evaluations of postdredging cores) that undisturbed residuals had been removed (but prior to additional cleanup pass redredging for generated residuals).

Mass balances were performed for individual dredge management areas by multiplying by the mass-per-area (MPA) of the corresponding cores. The MPA of each core was calculated as described in Equation 1:

$$\text{MPA} = \sum_{i=1}^{n} (C_i \times d_{\text{dry},i} \times l_i),$$

where $i =$ number of core segments, $C_i =$ contaminant concentration in each core segment, $d_{\text{dry},i} =$ in situ dry density in each core segment, and $l_i =$ length of each core segment.

The mass of generated residuals for each project was calculated by summing the products of the MPA calculated above by the corresponding dredge management areas ($A_i$; Eqn. 2):

$$M_{\text{generated residuals}} = \sum_{i=1}^{n} \text{MPA}_i \times A_i.$$  \hspace{1cm} (2)

The percentage of the initial predredging contaminant mass resulting as generated residuals was calculated as follows (Eqn. 3):

$$\text{Percent residual} = \frac{M_{\text{generated residuals}}}{M_{\text{predredge}}} \times 100.$$  \hspace{1cm} (3)

The results of the mass balance calculations for each construction season of the 4 robust dredge characterization projects is summarized in Table 1. The calculated generated residual contaminant mass (percent residual calculated in Eqn. 3) ranged between 1% and 13% of the contaminant mass in the original design prism.

GENERATED RESIDUAL PROJECTIONS

As discussed in the FORMATION OF GENERATED RESIDUALS section, Tiwari and Hayes (2012) identified sidewall sloughing and failure as a primary mechanism for residual generation, and also noted that the sloughing angle varies with sediment fluidity or density. To further examine this relationship, the generated residual calculations (percent residual calculated in Eqn. 3 and summarized in Table 1) are plotted in Figure 5 relative to the average in situ dry bulk density of the design cut. Key observations from this evaluation are summarized as follows:

• Regression analysis of the robust dredge characterization project data reveals a statistically significant ($P < 0.01$) linear relationship between the magnitude of generated residuals and the in situ dry bulk density of the design dredge cut. The best-fit linear regression equation of the multiple season averages from individual robust dredging projects is presented in Figure 5, consistent with early environmental dredging project data reported by Patmon and Palermo (2007):

$$R_g = -0.086d + 0.131,$$  \hspace{1cm} (4)

where $R_g =$ generated residuals (% of dredge prism mass), and $d =$ dry bulk density of the dredge prism (g/cm$^3$).
| Robust environmental dredging characterization project | Dredging years | Dredging volume (m$^3$) | Primary dredging equipment | Dredge type | Average in situ dry bulk density of design cut (g/cm$^3$) | Generated residual mass (mass balance) (% of dredge cut) |
|------------------------------------------------------|----------------|------------------------|-----------------------------|-------------|----------------------------------------------------------|--------------------------------------------------------|
| 1 Ashtabula River (OH, USA)                           | 2007           | 11 000                 | 20-cm articulated cutterhead | Hydraulic   | 1.23                                                     | 1.3                                                    |
| 2 Fox River (WI, USA)                                 | 2009           | 417 000                | 20- and 30-cm articulated cutterhead | Hydraulic   | 0.35                                                     | 11.0                                                   |
| 3 Fox River                                           | 2011           | 180 000                | 20- and 30-cm articulated cutterhead | Hydraulic   | 0.36                                                     | 13.1                                                   |
| 4 Fox River                                           | 2012           | 605 000                | 20- and 30-cm articulated cutterhead | Hydraulic   | 0.35                                                     | 9.2                                                    |
| 5 Fox River                                           | 2013           | 433 000                | 20- and 30-cm articulated cutterhead | Hydraulic   | 0.47                                                     | 11.9                                                   |
| 6 Fox River                                           | 2014           | 417 000                | 20- and 30-cm articulated cutterhead | Hydraulic   | 0.39                                                     | 8.1                                                    |
| 7 Fox River                                           | 2015           | 393 000                | 4-m$^3$ enclosed clamshell     | Mechanical  | 0.36                                                     | 4.1                                                    |
| 8 Fox River                                           | 2011           | 275 000                | 4-m$^3$ enclosed clamshell     | Mechanical  | 1.28                                                     | 5.8                                                    |
| 9 Hudson River (NY, USA)                              | 2012           | 495 000                | 4-m$^3$ enclosed clamshell     | Mechanical  | 0.97                                                     | 3.4                                                    |
| 10 Hudson River                                       | 2013           | 451 000                | 4-m$^3$ enclosed clamshell     | Mechanical  | 0.96                                                     | 2.6                                                    |
| 11 Hudson River                                       | 2014           | 408 000                | 4-m$^3$ enclosed clamshell     | Mechanical  | 0.96                                                     | 1.10                                                   |
| 12 Hudson River                                       | 2015           | 165 000                | 4-m$^3$ enclosed clamshell     | Mechanical  | 0.97                                                     | 3.4                                                    |
| 13 Esquimalt Harbour (BC, Canada)                     | 2013–2014      | 145 000                | 8-m$^3$ enclosed clamshell     | Mechanical  | 0.97                                                     | 2.6                                                    |
Whereas some operational factors are apparent (see further in this section), the magnitude of generated residuals appears to be largely independent of the dredge equipment used; generated residuals are primarily related to site-specific in situ characteristics of the dredged sediment. That is, dredging sediments with relatively low in situ density (approaching fluid mud densities) results in greater generated residuals. Note that the same 20-cm–diameter articulated cutterhead hydraulic dredge (and operated by the same dredging contractor) was employed on both the Ashtabula River and Lower Fox River projects, which had both the highest and the lowest in situ dry bulk densities (averaging 1.23 and 0.33 g/cm$^3$, respectively) of the robust dredge characterization projects. Corresponding average generated residuals were approximately $7 \times$ lower in the Ashtabula River compared to the Lower Fox River (1.3% versus 9.6%, respectively), consistent with the Figure 5 regression.

On both the Hudson River and the Lower Fox River projects, operational BMPs generally improved over the construction periods, resulting in approximate 2-fold reductions of generated residuals over the multiple years of implementation (see Figure 5 and Table 1). These improvements may be attributable to a range of operational improvements, including decreasing the number of dredge passes to achieve cleanup, greater operator experience and skill, and other factors.

When combined with site-specific design data on the thickness, in situ dry bulk density, and mass-weighted average sediment concentration of the design cut, and projecting a typical 20% reduction in the dry bulk density of the dredge prism sediment due to dredging operations (USEPA 2010), the regression equation summarized in Equation 4 and plotted on Figure 5 can be used to reasonably project generated residual characteristics on future environmental dredging projects.

**GENERATED RESIDUAL MANAGEMENT**

The robust dredge characterization project data summarized in previous sections demonstrate that, irrespective of the dredge equipment or operational BMPs employed, residuals will be generated during all environmental dredging projects. Site-specific sediments with lower in situ dry densities will generally result in greater amounts of generated residuals from dredging. Because lower density generated residuals can be subject to resuspension and transport for days following dredging (e.g., see Figure 4), upfront development and rapid implementation of residual management strategies are needed to improve both protectiveness and cost efficiency. Depending on the thickness, density, and chemical concentrations of the residual layer, as well as other site conditions (e.g., hardpan, proximity to utilities), effective residual management options include the following:

- Monitored natural recovery can be a protective residual management option at sites where future deposition is projected to be clean and rapid, and where relatively thin layers of generated residuals are present with concentrations only marginally above remedial action levels (e.g., within 2-fold).
- Sand covers have been demonstrated to be a very effective residual management option; postdredging placement of 10- to 15-cm–thick layers of clean sand was used extensively on all 4 robust dredge characterization projects listed in Table 1. On the Lower Fox River, approximately 50% of the dredge areas were covered with a 15-cm–thick sand layer, protectively limiting the potential for resuspension and transport of generated residuals. Even if the sand ultimately mixes into underlying sediments (Figure 3), thin covers have been demonstrated...
to protectively address generated residual concentrations that are up to 10-fold higher than remedial action levels, also providing a stable substrate that improves postdredging habitat functions. Where higher generated residual concentrations are encountered, engineered isolation caps or cleanup pass redredging may be needed.

- Cleanup pass redredging has proven effective in some situations, such as to remove a thin layer of generated residuals that exceed remedial action levels by several orders of magnitude, or to remove a deeper deposit of undisturbed residuals that may have been missed by the initial site characterization. On the Lower Fox River, approximately 20% of the dredge areas were redredged with a single cleanup pass, and then covered with a 15-cm–thick sand layer, as necessary. Because dredging operations reduce the density of in situ sediments (USEPA 2010), cleanup pass dredging of generated residuals becomes less effective (higher % of generated residuals; Figure 5) with each pass, resulting in inefficient and costly operations.

Many of the more recent environmental dredging projects, including the Hudson River project, have successfully utilized complex residual management decision frameworks, integrating a range of site-specific decision criteria. Upfront development, agreement, and automation of the residual management decision framework resulted in significant cost and time savings by reducing idle equipment time and protectively limiting the potential for resuspension and transport of generated residuals. The automated system used on the Hudson River project quickly generated accurate work products (e.g., summary tables, figures, and quality control reports) and removed subjectivity in the data evaluation, increasing stakeholder confidence in the outcomes.

The automated system developed for the Hudson River project comprised 2 modules: a data analysis module and a geospatial analysis module. Inputs to the system included databases with postdredging bathymetry, analytical chemistry data provided by the analytical laboratory (the electronic data management system also performed an automated validation of the data), information on the presence of clay and/or rock within the dredge area, and geospatial data in the form of shapefiles. The modules performed area and volume calculations, analyzed bathymetry data, and produced final geospatial files and summary maps, which were provided to the construction team in real time. The entire process of calculating statistics and developing summary tables and figures was usually accomplished in less than 2 h from the release of data, facilitating rapid residual management decision making and implementation. Sand cover placement or other residual management operations on the Hudson River project were often performed within a day of dredging completion. The automation resulted in significant overall cost savings and improved the protective (and transparency) of residual management operations.

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Data Accessibility—All data reported in this article are publicly available on websites maintained by the US Environmental Protection Agency, state agencies, and other federal agencies as summarized in the article and references.

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