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Research article

Early decision framework for integrating sustainable risk management for complex remediation sites: Drivers, barriers, and performance metrics

Melissa A. Harclerode [a, *], Tamzen W. Macbeth [b], Michael E. Miller [c], Christopher J. Gurr [d], Teri S. Myers [e]

[a] CDM Smith, 110 Fieldcrest Avenue, PO 8, Floor 6, Edison, NJ 08837, USA
[b] CDM Smith, 50 West 14th Street, Suite 200, Helena, MT 59601, USA
[c] CDM Smith, 231 Baker Road, Shutesbury, MA 01072, USA
[d] CDM Smith, 14 Wall Street, 17th Floor, New York, NY 10024, USA
[e] CDM Smith, 411 Aviation Way, Suite 230, Frederick, MD 21701, USA

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ABSTRACT

As the environmental remediation industry matures, remaining sites often have significant underlying technical challenges and financial constraints. More often than not, significant remediation efforts at these "complex" sites have not achieved stringent, promulgated cleanup goals. Decisions then have to be made about whether and how to commit additional resources towards achieving those goals, which are often not achievable nor required to protect receptors. Guidance on cleanup approaches focused on evaluating and managing site-specific conditions and risks, rather than uniformly meeting contaminant cleanup criteria in all media, is available to aid in this decision. Although these risk-based cleanup approaches, such as alternative endpoints and adaptive management strategies, have been developed, they are under-utilized due to environmental, socio-economic, and risk perception barriers. Also, these approaches are usually implemented late in the project life cycle after unsuccessful remedial attempts to achieve stringent cleanup criteria. In this article, we address these barriers by developing an early decision framework to identify if site characteristics support sustainable risk management, and develop performance metrics and tools to evaluate and implement successful risk-based cleanup approaches. In addition, we address uncertainty and risk perception challenges by aligning risk-based cleanup approaches with the concepts of risk management and sustainable remediation. This approach was developed in the context of lessons learned from implementing remediation at complex sites, but as a framework can, and should, be applied to all sites undergoing remediation.

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1. Introduction

More than forty years after the first environmental legislation was passed initiating cleanup programs, significant progress has been made in improving the environment and human health. However, a subset of contaminated sites requires disproportionate amounts of funding and resources to conduct "successful" remediation. These "complex sites" often have significant underlying technical challenges and span the spectrum of common sources and contaminated media, from groundwater to sediments, dry cleaners to uranium mines, and organic to inorganic contaminants. Cleanup of complex contaminated sites to promulgated regulatory standards can cost billions of dollars, leave large environmental footprints, and take decades, centuries or longer to complete (NAS, 2012; USEPA, 2004; Vogel, 2015). Furthermore, at many complex sites, the environmental, economic, and social costs of the remediation appear disproportionately large compared to measurable benefits (i.e., risk reduction) to human health and the environment (ESTCP, 2011; Farkas and Fragione, 2010; Geosyntec, 2004; Hadley and Ellis, 2009; Hadley et al., 2014; NAS, 2012; NRC, 2005; 2013).

The remediation community has responded to the challenge of complex site remediation by developing approaches for evaluating alternative endpoints (other than regulatory standards) and

* Corresponding author.
E-mail address: harclerodema@cdmsmith.com (M.A. Harclerode).

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adaptive management strategies. These approaches are herein referred to as "risk-based cleanup approaches"; defined as strategies implemented to manage risk, while continuing to protect human health and the environment. Guidance and publications on risk-based cleanup approaches have been developed within both United States (US) federal and state agencies (US AFCEE, 2005; CRWQCB, 2009; CDPHE, 2014; MDNR, 2006; USEPA, 1993, 2005; 2010), industry-specific professional organizations (ITRC, 2011a; 2012), research entities (ESTCP, 2011; NRC, 2013), as well as internationally (Bardos et al., 2016; CLARINET, 2002; NEPC, 2013; NICOLE, 2010; Gormley et al., 2011. In addition, published case studies highlight significant cost savings and reductions in environmental impacts by implementing a risk-based cleanup approach (ESTCP, 2011; Foran et al., 2015; Pizzol et al., 2015; and Thavamani et al., 2015).

Even though risk-based cleanup guidance and published case studies showing successful implementation are available to remediation professionals, this remediation approach is currently underutilized in the US. Risk-based cleanup guidance is often criticized for its shortcomings (Foran et al., 2015), which subsequently prevent or delay the consideration of such approaches. These shortcomings, from a US perspective, include the lack of frameworks available for developing site-specific cleanup objectives that are reflective of both primary and secondary risk management objectives, site characterization without regard to the intended remedy or future use for the site (Hadley et al., 2014), lack of alternative remedy performance metrics (Geosyntec, 2004; NRC, 2005), lack of consideration for stakeholder needs (Foran et al., 2015), and the absence of sustainability considerations. Because of these challenges, the risk-based approaches are often only utilized once remediation efforts have failed to meet promulgated cleanup standards. In other words, risk-based cleanup approaches are commonly viewed as a "last resort" option in the US. Ideally, risk-based approaches would be identified and evaluated early in all remediation project life cycles, thereby avoiding unsustainable and unjustified consumption of resources during remedy implementation.

1.1. Problem statement

The concept of sustainable remediation, "broadly defined as a remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of limited resources" (SURF, 2009), is interrelated with the risk-based cleanup approach. Presently, the consideration of sustainability for remediation projects is primarily focused on identifying unsustainable impacts from proposed remedial approaches, specifically in the United States where common practice is to either "green" the remedy or select a remedy that has the smallest unsustainable footprint. Sustainability and risk management are rarely considered at the process level of site characterization and remedy selection to ensure secondary performance metrics and stakeholder needs are accurately defined and integrated into project objectives. The consideration of sustainability and risk management late in the project life cycle results in the wasteful use of resources and related global impacts, leading up to remedy evaluation as well as failed remediation attempts. In addition, opportunities to reach a more sustainable community, such as re-use of treated groundwater in water stressed regions, revitalizing ecosystem services, and increasing the asset value of the contaminated land, are overlooked.

A sustainable risk management approach is needed to evaluate interrelations among the three dimensions of sustainability and its interrelatedness to risk management. In this paper, we attempt to develop a foundational framework to define and integrate sustainability and risk management objectives early in a complex project's life cycle to move towards a more sustainable state. In addition, it is important to note that the concepts of sustainable remediation and risk management are not independent of each other. As presented in the framework and discussion, sustainable remediation and risk management objectives often overlap, share drivers and barriers to implementation, and have the common goal of efficiently utilizing resources to protect human health and the environment.

2. Materials and methods

A comprehensive literature review was conducted to identify current guidance on risk-based approaches. Each guidance was reviewed for the following: drivers and barriers to sustainable risk management, performance metrics to measure risk reduction and sustainable attributes of cleanup, and tools used to track progress towards achieving sustainable risk management objectives. The purpose of the literature review was to also understand the current and potential role of sustainable risk management within the remediation community and regulatory programs. Collectively, this body of information was used to build a framework that integrates sustainable remediation and risk management practices early in the project life cycle to address the environmental, socio-economic, management, and risk perception barriers for acceptance of risk-based cleanup approaches.

2.1. Literature and case study review

A summary of the guidance and publications on risk-based cleanup approaches pertaining to adaptive management and alternative endpoints is provided in Table 1. Guidance on developing risk-based screening values, derived from equations combining exposure assumptions with toxicity data, (ITRC, 2005) was not included as part of the literature review. Findings of the review were compiled into the following five categories:

- *Risk-based cleanup approaches* are alternative endpoints and adaptive management strategies implemented to manage risk, while continuing to protect human health and the environment.
- *Barriers* are environmental, socio-economic, and/or risk management challenges which block consideration and implementation of sustainable risk management approaches.
- *Drivers* are site-specific characteristics that support consideration of sustainable risk management approaches.
- *Performance metrics* quantify how the action will lead to measurable increased protection for public health and the environment, thus leading to the development of targets or objectives (Hadley et al., 2014) that offer reductions in risk and unsustainable impacts.
- *Tools* evaluate performance metrics used to track the success of sustainable risk management approaches.

Barriers and drivers were further divided into three overarching categories: physical/environmental, socio-economic, and risk management, to illustrate the alignment risk-based cleanup approaches have with risk management and sustainable remediation practices. Risk assessment is a thoughtful process reliant on measurement and analysis of the most relevant system parameters to ultimately predict ecosystem, including human, vulnerability and resiliency (Di Giulio and Benson, 2002; Stahl et al., 2008). Risk management is a practice that uses risk assessment as a tool to support remediation objectives, using both primary (e.g., protection of human health and the environment) and secondary (e.g., efficiency, timeliness, cost-effectiveness) criteria (ITRC, 2012).

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