Towards Green and Sustainable Remediation of Contaminated Site

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ABSTRACT Traditional site remediation approaches often focus on reducing the contaminant levels to the risk-based levels at low cost in a short period of time. In contrast to a traditional remediation approach, *reen and sustainable remediation (GSR)* is a holistic approach to remediation that also minimizes ancillary environmental impacts. The GSR approach addresses a broad range of environmental, social and economical impacts during all remediation phases. The objective of GSR is to achieve remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water, and soil quality through reduce emissions and other waste burdens. GSR also simultaneously encourages the reuse of remediated land and increased long-term financial returns for investments. Though the potential benefits of GSR are enormous, many environmental professionals and project stakeholders do not utilize GSR technologies because they are unaware of methods for selection and implementation. However, with continued public awareness of sustainability issues, GSR will increasingly be pursued. This paper describes the decision framework including the metrics to assess sustainability of GSR, reviews the potential GSR technologies, and finally highlights the challenges in promoting GSR in practice.

INTRODUCTION

Traditional risk-based site remedial approach is based on: (1) the effectiveness and appropriateness of the particular remediation method to meet the remedial goals; (2) ease of implementation; (3) remediation costs; and (4) remediation timeframe. Such an approach is not always sustainable because it does not account for broader environmental impacts such as extraction and use of natural resources, wastes created, and energy use and related greenhouse gas (GHG) emissions for on and off-site operations, including on- and off-site transportation of equipment and materials. Thus, this approach does not explicitly account for the *net environmental benefit* when all relevant environmental parameters are considered. To address this, a focus on green and sustainable remediation (GSR) approach has begun to emerge.

GSR is a holistic approach to protect human health and the environment while minimizing environmental side effects. Goals include (1) minimizing total energy use and promoting the use of renewable energy for operations and transportation; (2) preserving natural resources; (3) minimizing waste generation while maximizing materials recycling, and (4) maximizing future reuse options for remediated land (USEPA, 2008; Ellis and Hadley, 2009). In addition to the environment, GSR maximizes the social and economic benefits (often all known as the triple bottom line) associated with a project. Various government, industry, and professional organizations both in the United States and worldwide are actively engaged in developing various initiatives and activities with the ultimate goal of promoting GSR. This paper presents the GSR decision framework that incorporates sustainability metrics and assessment tools. GSR technologies available to remediate contaminated sites are described, and the challenges and opportunities in implementing GSR in practice are discussed.

DECISION FRAMEWORK

A GSR framework represents the confluence of environmental, social and economic factors for decision-making. The framework concept refers to a range of practices and objectives that can be integrated into a project to increase sustainability. Unfortunately, a standardized decision framework has not been developed yet, but it should address at least the following factors:

- Reduced energy consumption associated with site remediation, the manufacture of consumables, and the management of residual soil and groundwater impacts. Additionally, renewable energy sources should be incorporated when possible.
- Minimized GHG emissions should be undertaken through the use of best management practices, including in-situ GHG sequestration within soils and/or vegetation.
- The use of remedial technologies that do not require on-site or off-site waste disposal.
- The use of remedial technologies that utilize recycled and/or reclaimed water sources, thereby reducing the need for fresh water. Additionally, technologies that promote the reuse and recycling of by-product materials should be incorporated.
- When appropriate, the use of remedial technologies or strategies that that do not restrict the potential future land use of a site.

A framework based on these factors is a critical component to facilitate the selection, design, and implementation of sustainable remedies at contaminated sites. By incorporating site-specific information, various potential remedial alternatives may be identified. Each alternative implementation is carefully assessed for sustainability factors, such as greenhouse gas emissions, energy and materials consumption, land use, and water use. To assess these factors, relevant and beneficial sustainability metrics need to be defined and tools to quantify them are required.

Sustainability Metrics

In general, the metrics used for GSR performance have not been standardized. Traditional remediation metrics include remediated area (m^2 or sq. ft.), mass of treated contaminants (kg or tons), and mass of treated soil (kg or tons). Complementing these metrics, performance of GSR should be measured by:

- Energy consumption (kWh or BTU)
- Water consumption (m^3 or gallons)
- Waste generation (kg or tons)
- Greenhouse gas emissions (carbon dioxide equivalents or tons)
- Air pollutants (kg or tons)

In addition, positive actions, such as renewable energy use, materials recycling, natural resources preservation, site redevelopment and re-use, ecological restoration, etc., should also be considered.

Environmental intensity indicators may better serve as metrics for evaluations; such indicators include:

- Energy per unit treated mass (kWh/kg)
- Water used per unit treated soil mass (m^3/kg)
- Carbon dioxide emissions per unit treated soil mass (t/kg).

The associated environmental costs may be indicated by cost per unit remediated area ($/$m^2$), cost per unit treated contaminant mass ($/kg), and cost per unit treated soil mass ($/kg).

Assessment Tools

Qualitative and quantitative assessment tools are being developed to calculate sustainability metrics that consider all factors for GSR design and implementation. These tools can range from simple decision trees and Excel Spreadsheets to complex full life-cycle assessments. Qualitative assessment tools facilitate the screening of different remediation technologies based on potential impacts on the environment, society, and economics. Several public agencies have developed to preliminary assess potential remedial technologies, including:

- California DTSC developed a matrix that ranks the material and energy inputs and outputs associated with all elements of a remedial method;

- Illinois EPA developed a two-page matrix that identifies the environmental benefits of each activity in remediation in terms of air, water, land, and energy;
- Minnesota Pollution Control Agency created an Internet-based interactive toolkit that includes a decision tree and checklist of factors to consider in remedial method selection.

Recently, industry and government agencies have started to develop tools that specifically quantify the impacts of remediation technologies on the environment, society, and economics. For example, GSI Environmental Inc. developed the Sustainable Remediation Tool (SRT) for the Air Force Center for Engineering and the Environment (AFCEE) to assist environmental professionals in incorporating sustainability concepts in their remedial method decisions. The Microsoft Excel-based SRT estimates sustainability metrics for selected specific technologies, including carbon dioxide emissions, total energy consumed, change in resource service, technology cost, and safety/accident risk. SRT can be implemented as a preliminary Tier 1 analysis or a more detailed Tier 2 analysis based on user-defined, detailed, site-specific criteria.

EPA's Pollution Prevention Program developed a GHG Calculator tool to help quantify GHG reductions categories such as electricity conservation and water conservation. Because there is no universally accepted way of calculating a carbon footprint, dozens of carbon calculators have become prevalent over the past few years, creating confusion and inaccurate information. It is recommended to use a life cycle assessment (LCA) to properly analyze carbon footprint and other impacts.

LCA can provide a quantitative approach that provides an objective, scientific, and numerical basis for decision-making of GSR technologies. LCA can be used to:

- Provide benchmarking for existing systems;
- Retrospectively identify opportunities to decrease impacts in future remediation;
- Retrospectively identify where specific improvements would be most advantageous;
- Compare different remediation options during the technology selection process.

LCA is a complex environmental assessment tool that requires significant data that are often expensive or hard to find. The selection of boundaries for LCA is also a difficult task. However, LCA is flexible, allowing for simplification based on the specific application, simplified assumptions, and defined assessment boundaries. Thus, LCA can be made as an elaborate research tool or a "quick-and-simple" assessment tool.

The Economic Input-Output Life Cycle Assessment (EIO-LCA) method provides guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain (CMU-GDI, 2009). This method has been used extensively for product development, but its application to assess sustainability parameters of site remediation has been suggested.

Applications of LCA for the remedial strategy optimization at contaminated sites are relatively scarce. This is mainly attributed to a lack of LCA training for environmental remediation professionals, modeling, lack of required input and output data, and significant time requirements. LCA also requires interdisciplinary collaboration. However, Because of the necessity for simultaneous fulfillment of multi-faceted aspects of GSR, LCA can serve as the most logical decision-making tool for comparative evaluation of alternative remedial options with the baseline (traditional) remedial option.

GSR TECHNOLOGIES

The key principles and factors of GSR should be incorporated during all phases of a remediation program, including (1) site investigation, (2) remediation system selection, design, construction, and operation, (4) monitoring, and (5) site closure and determination of appropriate future land use. The use of the USEPA's Triad decision-making approach is highly recommended for site investigations (USEPA, 2001). This method consists of three interrelated components; (1) systematic project planning, (2) dynamic work strategies, and (3) real-time measurement technologies to reduce decision uncertainty and increase project efficiency. Appropriate sustainability principles can be incorporated into site characterization activities. For example, direct push technologies, geophysical techniques, and passive sampling and monitoring techniques can reduce waste generation, consume less energy, and minimize land and ecosystem disturbance.

It can be challenging to incorporate sustainability parameters into the process of selecting remedial technologies. A wide range of ex-situ and in-situ remediation technologies have been developed and implemented at contaminated sites (Sharma and Reddy, 2004). Some technologies, such as pump-and-treat operations and incineration, are known to be energy-intensive and may not meet GSR criteria. An ideal remediation technology (and all associated on-site or off-site actions) should aim to:

- Minimize the risk to public health and the environment in a cost-effective manner and a reasonable time period.
- Eliminate the potential for secondary waste and prevent uncontrolled contaminant mass transfer from one phase to another.
- Provide an effective, long-term solution.
- Minimize the impacts to land and ecosystem.
- Facilitate appropriate and beneficial land use.
- Minimize or eliminate energy input. If required, renewable energy sources (e.g., solar, wind, etc.) should be used.
- Minimize the emissions of air pollutants and GHGs.
- Eliminate fresh water usage while encouraging the use of recycled, reclaimed, and storm water. Further, the remedial action should minimize impact to natural hydraulics water bodies.
- Minimize material use while facilitating recycling and/or the use of recycled materials.

Technologies that encourage uncontrolled contaminant partitioning between media (i.e., from soil to liquid or from liquid to air) or those generate significant secondary wastes/effluents are not sustainable. Rather, technologies that destroy the contaminants (such as bioremediation, chemical oxidation/reduction), minimize energy input, and minimize air emissions and wastes, are preferred. In-situ systems are often attractive, as they typically minimize greenhouse gas emissions and limit disturbance to ground surface and the overlying soils.

A variety of remedial technologies satisfy core GSR criteria; however, the project life cycle for a specific technology should be considered to determine if it is appropriate for use at a given site. For example, ex-situ biological soil treatment is considered a promising GSR technology; however, the impacts of transporting soil (if off site treatment is required) should be evaluated. Similarly, enhanced in-situ bioremediation is also considered an attractive GSR technology, but the cumulative impacts that occur during its characteristically long treatment duration should be compared to those of other active remediation that require less time. In general, passive containment systems such as phytoremediation and permeable reactive barriers utilize little mechanical equipment and minimize energy input. Additionally, these systems result in minimal waste/effluent to manage. While active containment systems can prevent contaminant migration, receiving waters can be degraded if migration occurs. Finally, in-place management using monitored natural attenuation with engineering controls is often compared with a more aggressive excavation and disposal scenario. In-place management eliminates GHG or other emissions; however, excavation and disposal allows for rapid remediation and often eliminates the need for engineering or institutional controls.

A single remediation technology often cannot cost-effectively address the technical challenges posed by contamination at a particular site. Based on the site-specific conditions, multiple technologies may be sequentially or concurrently used for remediation. Further, technologies not typically considered sustainable may be combined with other technologies to develop multi-component remedial programs that are sustainable.

Some popular technologies used to treat residual contaminant concentrations are not considered effective in treating source remediation. Groundwater plumes with moderate to high dissolved contaminant concentrations may require a brief implementation of active remediation technologies to expedite contaminant mass reduction. Alternatively, many technologies appropriate for source removal are often ineffective in treating residual or lower concentrations that result from reduced contaminant diffusion and dissolution. Under such conditions, GHG emissions and energy usage associated with aggressive technologies may outweigh further contaminant mass removal/destruction. Under such conditions, a technology with lower energy requirements and emissions may be used to treat residual contamination. Large dilute groundwater plumes may be treated using lower-energy passive technologies; this may extend the duration of the remediation program, but it will reduce overall net impacts to the environment.

The duration of the remediation program can itself be a major governing factor in remediation system selection. Remediation technologies such as bioremediation may require lower energy input, but they require longer treatment time. Further, given the duration of the remediation, cumulative energy use can often be greater as compared to a shorter but energy-intensive remediation program. Other anticipated or unanticipated side effects, such as incomplete mineralization, can render these as ineffective alternatives. Further, even energy-intensive aggressive technologies, such as thermally enhanced remediation, may become attractive from a sustainability standpoint if renewable energy sources are used.

Opportunities exist for reducing energy and carbon footprints from existing remediation systems. In particular, energy efficiency can be maximized by optimizing existing treatment systems, critically evaluating design, and upgrading equipment. In addition, alternative sources of energy, including solar, wind, landfill gas, biomass, geothermal, tidal/wave, and cogeneration can be incorporated into existing systems. A growing number of existing projects have started to use solar or wind energy sources.

CASE STUDIES

USEPA (2008) presents several case studies that use GSR for site remediation. These case studies document use of renewable energy sources, reduction in waste generation, recycling and reuse of materials, and beneficial land end use. Ellis and Hadley (2009) also present selected case studies and concluded that the applications of LCA for site remediation decisions are scarce. Diamond et al. (1999) developed a life-cycle framework specifically applicable to site remediation. Page et al. (1999) presented a comparative study to demonstrate the application of this framework. Volkwein et al. (1999) presented an LCA combined with the results of a risk assessment to assess impacts of three remedial options (dig-and-haul, installation of an asphalt cap, and thermal/biotreatment) for a contaminated site. Godin et al. (2004) performed a comparative LCA to assess four remedial options (dig and haul, excavation and treatment, excavation and incineration in a cement kiln, and leaving the soil in place). Toffoletto et al. (2005) described an LCA of ex-situ bioremediation to optimize it to reduce the environmental impact.

Cadotte et al. (2007) applied LCA to evaluate in-situ and ex-situ methods to remediate a LNAPL site. Optimal combinations of soil and groundwater technologies were assessed. Lesage et al. (2007) used a LCA approach to evaluate impacts of a brownfield site remediation and the reuse of the property. Higgins and Olsen (2009) performed a comparative LCA of pump and treat and permeable reactive barrier (PRB) technologies and demonstrated that PRB was advantageous for net environmental benefit.

CHALLENGES AND OPPORTUNITIES

Several challenges and opportunities exist in promoting GSR in practice, including a lack or absence of: (1) education and training for stakeholders; (2) guidance documents with clear and consistent definitions; (3) standardized sustainability metrics and validated evaluation tools; (4) well defined frameworks and processes to evaluate sustainability; (5) well documented pilot studies/case studies involving sustainable remedies; (6) incentives to adopt sustainable remedies; (7) funding to support the research and development of sustainable approaches; and (8) specific regulations requiring GSR.

CONCLUSION

GSR is a rapidly evolving approach for the remediation of impacted sites. GSR aims to achieve remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water, and soil quality through reduced emissions and other waste burdens. The development of a GSR framework will allow the selection and optimization of all phases of remedial action, leading to a net benefit to environment, society and economy. There is great interest and urgency among environmental professionals to incorporate the beneficial aspects of sustainability into the remediation system selection and implementation.

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