Incorporation of green remediation into soil and groundwater cleanups

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The remediation of contaminated soil and groundwater is essential toward the development of a sustainable society. However, remediation activities at various stages will also inherently add a significant burden of environmental footprints. Green remediation is thus increasingly recognized in the recent years by various regulatory agencies, responsible parties, remediation engineers, and various other stakeholders. This paper critically analyzes the evolution of green remediation and its context relating to various driving forces and potential impediments, the primary practices and opportunities to an increased sustainability in site cleanups, and quantitative sustainability evaluation tools employed to measure the greenness of soil and groundwater remediation technologies. Although the principles of green remediation are supported by the goals of several regulatory provisions in the U.S. and EU countries, there are not sufficient regulatory driving force and economic incentives to fully implement green practice in the remediation industries. Even though the incorporation of green remediation into contaminant cleanup can provide a better image for the responsible party, the negative side from the public may also exist because of the perception of selection preference to the less invasive cleanup technology (e.g., natural attenuation over pump-and-treat). The problems associated with the currently employed tools using life cycle assessment (LCA) also prevent the accurate comparison among various remedial options essential for the decision-makers. Lessons learned from several recent case studies on LCA are summarized in regard to its methodological flaws, such as subjective selection of functional units and impact categories, and inconsistent spatial and temporal boundaries. Current LCA methodology well quantified remediation options in the regional and global scale such as eutrophication, ozone depletion and global warming; however, with inherent issues of quantification and weighting, site-specific primary impacts of contaminated sites are often underestimated, which are often the driving force for site cleanups. A remediation sustainability index is proposed in the context of six core elements of green remediation. Finally, the opportunities, challenges and some future perspective for the incorporation of sustainable principles into the practice of cleaning up contaminated sites are discussed in the paper.

Introduction

To achieve the cleanup goal for contaminated soil and groundwater, the cleanup itself also adds a significant environmental footprint to the contaminated sites at the local to global scale. Green remediation is thus employed to minimize the environmental impacts by using sustainable best management practices (BMPs). The purpose of this paper is to critically analyze the current state of green remediation in the context of driving forces and potential impediments, the well-recognized BMPs for an increased sustainability at various stages of site cleanup, and the methodological issues associated with currently employed quantitative assessment tools to measure the sustainability of soil and groundwater remediation technologies. Lessons learned from limited case studies on the increased use and improved assessment of green remediation are discussed. Like other sectors, traditional cleanup technologies are facing paradigm shift from mere cost-effectiveness to holistic approach considering economic, social and environmental impacts. Some future perspectives and challenges are also discussed in the context of incorporation of green remediation.

Evolution of remediation technologies

The environmental remediation sector for the cleanup of contaminated soil and groundwater started in the late 1970s in the U.S., Canada and most of the European countries following the environmental movement.
In the U.S., for example, two federal regulations are the major players in regulating the cleanup of various contaminated sites, the Comprehensive Environmental Response, Compensation, and Recovery Act (CERCLA), and the Resource Conservation and Recovery Act (RCRA). These contaminated sites can be grouped into seven major cleanup programs or market segments that make up the national cleanup market (USEPA, 2004): National Priorities List (NPL, or Superfund), RCRA facilities, Underground Storage Tanks (UST), Department of Defense (DOD) sites, Department of Energy (DOE) sites, other (civilian) federal agencies, and states and private parties (including brownfields). Although environmental remediation activities in the U.S. account for a small fraction (0.036%) of the GDP, it represents an annual total of approximately $5 billion in 2006 (SURF, 2009).

The selection of remediation technologies has been traditionally based on the cost-effectiveness (capital and O&M costs, remedial efficiency and time) of the specific technique to meet the cleanup requirement without much consideration of the impacts beyond the site. It is therefore not surprising that more invasive and energy-intensive remediation technologies such as soil excavation, incineration, and pump-and-treat (Table 1) were the primary remedial options to cleanup Superfund sites since its inception of nation’s remediation programs. With the increasing recognition of the cost-effective issues, these “established” technologies have been gradually shifted to other remediation technologies around 1990, termed “innovative” remediation technologies, such as soil vapor extraction, in-situ bioremediation and natural attenuation.

Table 1: Evolution of environmental remediation technologies

<table>
<thead>
<tr>
<th>Period (approximate)</th>
<th>1970-</th>
<th>1990-</th>
<th>2000-</th>
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<tbody>
<tr>
<td>Examples of favorable technologies</td>
<td>Soil excavation / Incineration / Pump-and-treat</td>
<td>Soil vapor extraction / In-situ bioremediation / Natural attenuation</td>
<td>Holistic approach considering site characterization, design, construction, operation and monitoring</td>
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<td>Primary determinant for remedial selection</td>
<td>Effectiveness</td>
<td>Cost; Effectiveness</td>
<td>Cost; Effectiveness; Sustainability</td>
</tr>
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<td>Spatio-temporal boundary</td>
<td>Local; Short-term</td>
<td>Local; Long-term (generally)</td>
<td>Regional to global; Life-cycle</td>
</tr>
<tr>
<td>Pros and cons</td>
<td>More efficient (supposedly), invasive, but more costly</td>
<td>Less invasive and costly, but more time (generally)</td>
<td>A harmony balancing social, economic and environmental benefits</td>
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For the last decade since around 2000, however, an increased attention has been paid to the sustainability of contaminant remediation. A significant progress has been made in the sustainable remediation field during the last few years, specifically through the publication of guidance, strategies, and policies by government agencies (e.g., USEPA, 2008, 2009a, 2010, 2012), remediation practitioners, and industry associations (e.g., SURF, 2009). Sustainable remediation is thus 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). Organizations sometimes refer to green remediation, which can be defined as the practice of considering all environmental effects of remedy implementation and incorporating options to maximize the net environmental benefit of cleanup actions (EPA, 2008). Like the sustainability of other sectors, sustainable remediation is aimed to “create and maintain conditions, under which human and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations” in accordance with President Obama’s Executive Order 13514.

Remediation sustainability evaluation: lessons learned from published case studies

The evaluation of remediation sustainability is a prerequisite for the success of green remediation incorporation. Over two dozens of software tools (EAP, 2006), including risk assessment, impact assessment and benefit-cost analysis, are available for their potential uses in selecting and planning remediation technologies. However, life cycle analysis (LCA, also known as cradle-to-grave analysis) is among the most employed. First, LCA enables the estimation of the cumulative environmental impacts from all stages in the
product life cycle, often including impacts not considered in more traditional analyses such as raw material extraction, material transportation, and ultimate product disposal. Second, LCA offers a quantitative measure in identifying major environmental impacts at different life stages. Such quantitative information will provide insight into the improvements and adjustments toward sustainable practice prior to or during remediation activities (prospective LCA), or provide historical perspectives of completed remediation projects (retrospective LCA). Third, LCA provides objective comparison of various remedial actions (Table 2). For example, LCA results favor the reuse of remediation facility, short-distance transportation (in-situ over ex-situ), and biological over thermal or chemical remediation. LCA does not support long-term energy-consuming as well as active remediation techniques such as pump-and-treat (P&T), whereas it also reveals the shortcomings of some passive remedial techniques such as permeable reactive barrier (PRB). With key impact-contributing factor(s) identified, such as the right selection of reactive materials or construction methods and the materials in funnel-and-gate (F&G) systems, significant reduction in emissions and carbon footprints can be effectively achieved. LCA result is also in favor of the new technology such as horizontal directional drilling (HDD) over the traditional vertical drilling method using rotary augers.

Despite the widespread acceptance as an ISO’s standard (ISO 14040-43), LCA application in site remediation is still an area of new development. Several reviews (Morais and Delerue-Matos, 2010; Lemming et al., 2010; Suèr et al., 2004; Owssianiak et al., 2013) revealed a great LCA methodology discrepancy and raised concerns about LCA conclusions because remedial actions heavily depend on specific LCA methodology and assumptions made on the inventory data (Table 2). Although none of these investigators were able to offer solutions to critically improve the existing LCA methodology, they generally have consensus about the methodological issues of LCA, and agree that the use of an inadequate methodology may lead to misleading conclusions to the practitioners and decision-makers in the field of soil and groundwater cleanup.

The major methodological shortcomings can be grouped in two areas. The first is the lack of standard procedures to define function units, formulate temporal / spatial /geographical boundaries, and objectively select matrices and impact categories. Previous reviews indicated that many LCA studies have incomplete definition of functional units and failure of including all relevant secondary impact categories. Groundwater matrix, tertiary effects, and land use are commonly missed in evaluation. The second type of shortcoming is the lack of a robust quantitative approach to estimate and assign weights to various impacts (especially primary impact). While secondary impacts (e.g., global warming potential, ozone depletion, eutrophication, atmospheric emission) are relatively easier to quantify using available protocols, the quantification of primary impacts directly from the remediation service at the local setting is much harder owing to the complex nature of toxicant fate and exposure model and subsurface heterogeneities. As a result, primary impacts are oftentimes left less scrutinized during the LCA examination. Moreover, a weighting between primary and secondary impacts has not been adequately addressed in almost all the LCA studies to date. From the sustainable perspective, secondary impacts are important; however, it is arguable that primary impacts can even be more important because minimizing the toxicant levels is the initial motivation behind all the remediation activities. This is partially because stakeholders such as the local responsible parties are the ones who pay for the remediation, not others who are located remotely from the contaminated site.

Table 2: Summary of selected case studies on the life cycle assessment of green remediation technologies

<table>
<thead>
<tr>
<th>References</th>
<th>Remediation Technology Options</th>
<th>Description of major conclusions relevant to remedial options</th>
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<tbody>
<tr>
<td>Page et al. (1999)</td>
<td>Four life-cycle stages for the excavation and off-site disposal of a lead-contaminated site</td>
<td>Major emissions were identified to be 82-100% from clean backfill during the stage of raw materials acquisition; &gt;96% from site excavation during site processing; 75% during transportation of hazardous soil to landfill.</td>
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<td>Volkwein et al. (1999)</td>
<td>a. on-site ensuring; b. surface sealing with asphalt; c. decontamination</td>
<td>Option (a) (excavation and on-site redumping) is favorable over (c) (excavation followed by treatment) because of the less secondary impact and the shorter remediation time (1 vs. 25 months). Option (b) is unfavorable in respect to the primary (risk) and secondary</td>
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### Results


<table>
<thead>
<tr>
<th>Authors (Year)</th>
<th>Methodology</th>
<th>Findings</th>
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<tbody>
<tr>
<td>Toffoletto et al. (2005)</td>
<td>Ex-situ bioremediation (biopiles) of diesel contaminated sites: a. single-use facility; b. permanent facility</td>
<td>A permanent treatment center (b) is preferred over a single-use treatment facility (a) because of the significantly lower secondary impact. Global impacts increased significantly if the soil has to be transported to over 200 km from the site.</td>
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<td>Bayer and Finkel (2006)</td>
<td>a. P&amp;T (active); b. F&amp;G (passive)</td>
<td>For a former manufactured gas plant, P&amp;T is favorable in regard to human health impact. Decreasing impacts can be achieved in F&amp;G by changing the type of F&amp;G from sheet piles (with recycling after 30 years) to thin diaphragm walls.</td>
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<tr>
<td>Cadotte et al. (2007)</td>
<td>a. P&amp;T; b. all biological in situ; c. in situ biological-chemical oxidation; d. ex-situ biopiles</td>
<td>Option (a) was the worst in terms of primary impacts and Option (c) was the worst in terms of secondary impacts. Option (b) showed the least primary and secondary impacts but its treatment time was &gt;4 times longer than (c).</td>
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<tr>
<td>Higgins and Olson (2009)</td>
<td>a. Permeable reactive barrier; b. P&amp;T</td>
<td>The construction of ZVI medium drives the potential impacts of PRB, whereas operational energy demand drives the P&amp;T technology. A minimal longevity of 10 years is required to exert benefit of PRB over P&amp;S.</td>
</tr>
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<td>Suèr and Andersson-Sköld (2011)</td>
<td>a. phytoremediation; b. excavation-and-landfill</td>
<td>For a discontinued oil depot, option (a) using willow for biofuel production had greater environmental advantages compared to (b). Impacts from (a) were mainly from land use and though journeys of control personnel, whereas impacts from (b) were dominated by the landfill and the transport of contaminated soil and backfill.</td>
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<tr>
<td>Lemming et al. (2012)</td>
<td>a. long-term monitoring; b. in-situ enhanced ERD; c. ISCO with permagnate; d. long-term monitoring combined with AC at waterworks</td>
<td>For a TCE-contaminated site with a source zone located in a fractured clay till, options (a) and (b) are preferred due to lowest secondary impacts even though both have extended timeframe (700 vs. 90-200 yr, assuming VC can be avoided). Option (c) (80 yr) is not recommended because it caused the highest secondary impacts. Option (d) becomes unfavorable if AC is required. No options result in a net reduction in environmental impacts in terms of person equivalents. No environmental benefit from remediating the site.</td>
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<tr>
<td>Lubrecht (2012)</td>
<td>a. horizontal directional drilling (HDD); b. vertical auger drilling</td>
<td>Although not universally applicable or desirable, HDD prove to be a superior choice over vertical auger drilling to achieve sustainable and green remediation in terms of construction and operation.</td>
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**AC** = activated carbon; **ERD** = enhanced reductive dechlorination; **F&G** = funnel-and-gate; **ISCO** = in-situ chemical oxidation; **PRB** = permeable reactive barrier; **P&T** = pump-and-treat system; **TCE** = trichloroethene; **VC** = vinyl chloride; **ZVI** = zero-valent iron.

Results from LCA were also criticized because LCA outcomes are generally not in favor of resource-intensive but technologically effective (established) remediation technologies such as incineration and pump-and-treat (Table 2). In general, the negative impact of site remediation is due to energy consumption. For excavation combined with ex-situ treatment, the transport of contaminated soil to the treatment facility or landfill requires the most energy. For in-situ soil and groundwater treatment, pumping consumed the most energy (Suèr et al., 2004). Low energy (passive) systems are always favored, including bioremediation, phytoremediation, engineered wetland, biological permeable reactive barrier, and natural attenuation. It is possible that these systems indeed have the overall better environmental benefits toward sustainable...
development. Based on 9 case studies, Suèr et al. (2004) further indicated that bioremediation was the best, but it can be the worst if the secondary process of producing electron acceptors was included. Moreover, bioremediation also adds other footprints and technical incompetency (e.g., site-specific feasibility testing, operational instability, long-term monitoring need, and potential introduction of invasive species) that are not countered in the current LCA. Likewise, land use was especially important for certain remedial activities. Unfortunately, it is generally not considered in the current LCA.

Such apparently biased outcome from LCA might affect negatively on the incorporation of green remediation into contaminant cleanup because the public likely perceives the responsible party as the get-away approach from remediation. This is similar to the perception about natural attenuation even before the concept of green technology, as some people incorrectly assumed natural attenuation as a “do-nothing” approach. An extreme argument came from a case study from Lemming et al. (2012) who compared four remediation scenarios (Table 2) and concluded that none result in a net reduction in environmental impacts in terms of person equivalents, and no environmental benefit can be achieved from remediating the site.

On the other hand, the above conclusion may first sound erroneous as one can hardly imagine how the environmental benefit for the cleanup of a contaminated site can be exceeded by the adverse environmental footprint caused by remediation activity itself. This, however, might become obvious when one relates to an example of trichloroethylene (TCE)-contaminated aquifer containing dissolved TCE at a concentration of 1.5 mg/L, corresponding to only 1 gallon TCE released into 1 million gallons of groundwater (density of TCE = 1.5 g/cm3). The USEPA’s maximum contaminant level goal (MCLG) for TCE is zero based on the best available science to prevent potential health problems, whereas its enforceable regulatory standard, called a maximum contaminant level (MCL) is at 0.005 mg/L (or 5 ppb). In order to attain the MCL using pump-and-treat, remediation may take 10-20 years using a dozens of wells depending on the site hydrogeological conditions. Comparing the risk reduction from this minute TCE mass removal (1 gal = 5.7 kg TCE), the remediation footprint may become disproportionally high for such an extended period. In other words, a question may naturally arise, namely, is it worthwhile to cleanup this small quantity of TCE at the expense of significant environmental footprint? Put it in another way for a more familiar example of petroleum contamination, the valid question is still: Is it worthwhile to cleanup this small quantity of petroleum hydrocarbon for a duration of 2 years using P&T followed by SVE while the annual hydrocarbon fuel consumption is 10 times or more of that amount?

Challenges and opportunities for the incorporation of green remediation

The most notable challenges for green remediation practices lie in regulatory and economic drivers. Sustainable practices in contaminant remediation are not currently enforced by any regulatory provisions in the U.S. The U.S. EPA considers science-based green program a voluntary complement to its traditional “command-and-control” regulation of industry toward achieving environmental protection and sustainable development (Hjeresen et al., 2001). It is therefore important to recognize that the integration of sustainable framework into the current regulatory structure is the most essential. Besides, the lack of financial or certification incentive is another constrain limiting the innovation and adaption of sustainable remediation practice. Economic incentives can be in the form of tax incentives, or emission credits and trading.

The good news, however, is that at least two new driving forces can be identified for the incorporation of sustainable practices. The first is the increased awareness of sustainability in the society due to increasing concerns about global warming, climate change and other environmental effects. Corporate leaders also become more conscious about the regional and global impacts from their activities. The second motivation comes from within the industry, whose own desire is to improve its cost-saving (at least for some BMPs) and improve corporate own image of sustainability.

To facilitate the transition from traditional to sustainable remediation, well-defined technical guidelines as well as agreed-upon matrices should be developed in the near term and accepted by all stakeholders (SURF, 2009; EPA, 2008). The subjective selection of impact categories and their weighting during the sustainability evaluation is one major barrier and technical challenge for the introduction of sustainability. The subjective selection of sustainable matrices and impact categories make the comparison of remediation options less scientifically sound and useful to the decision-makers. The lack of scientifically sound weighting
criteria will make sustainability evaluation less trust-worthy for the practitioners to adopt. The importance of weighting is further exemplified in Figure 1.

As Figure 1 implies, the reduced primary impacts (risk) in the cleanup process is at the expense of increasing secondary impacts. In other words, removing aquifer contaminants will inadvertently add environmental footprint. For a monotonically decreasing primary impact along the remediation process (time, % mass removal, or restored groundwater volume), the secondary impacts due to the remediation activities increase accordingly. Here, both primary and secondary impacts are normalized to the same unit (e.g., the dollar amount from the risk or emission per unit mass of contaminant removed), they are consequently additive. If one assumes equal weight (1:1) between primary and secondary impact, then a hypothetical time of 38 years is need to reach a break point between these two types of impacts where the overall impact is at minimum. When a larger weight is assigned to the primary impact, the break point for the remediation effort increase to 50, 66, and 78 years corresponding to a weighting of 2:1, 5:1, and 10:1, respectively. This example illustrates how weighting can be an important consideration in LCA that can lead to very different conclusions of remedial strategies for the decision-makers. Although the exact weighting assignment is subjective to the compromised cost-benefit analysis, the point here is clear that the benefit from removing certain amount of contaminant (e.g., petroleum) is not the same as one adds to the secondary impact of the same amount of petroleum fuel during remediation.

Opportunities for sustainable practices existed long before the concept of green remediation. However, such opportunities for sustainable practice exist particularly for those resource-intensive remediation techniques. Elements of green remediation technologies vary depending on the stage of remediation and specific remedial option chosen. For illustration purpose, only pump-and-treat is briefly introduced below, since there are too many to give a full list of these site specific BMPs. The U.S. EPA has published a series of fact sheets regarding the green remediation BMPs for various remediation activities, beginning with site assessment / investigation and ending through remedy operation and closure of the whole life cycling.

BMPs start with site characterization. It may include the use of direct-push technology instead of rotary drilling rigs to reduce investigation derived wastes (IDW) from drilling fluids and cuttings; reuse of wells and subsurface bore-holes throughout investigation, remediation and long-term monitoring; use of field test kits whenever possible and select nearest analytical lab possible; use of geophysical tech, passive sampling
(air, sediment, groundwater), remote data collection; use of renewable energy powered systems; reuse of purged water, ash and spent carbon; use of non-phosphate detergents to decontaminate PPE.

Following site assessment, perhaps remedial selection stage has the most bearing on the integration of sustainability, particularly for those energy-intensive technologies. According to the U.S. EPA (2008), five energy-intensive technologies used for Superfund sites, in their decreasing order of the estimated annual average energy consumptions are: pump-and-treat (79.2%), thermal desorption (15.0%), multi-phase extraction (3%), air sparging (1.6%), and soil vapor extraction (1.1%). The total annual energy of these five cleanup technologies is estimated 6.18×108 kWh. By assuming a 1.37 lbs CO2 emitted into the air for each kWh of electricity generated in the U.S., the use of these five technologies at NPL sites in 2008 through 2030 is predicted to have CO2 emission totaling 9.2 million metric tons. This is equivalent to operating two coal-fired power plants for one year. A similar claim was also made for the remediation projects in New Jersey where the difference between two proposed remedies could be as high as 2% of the annual greenhouse gas emissions for the entire state (SURF, 2009).

At the design stage, opportunities to integrate green remediation strategies can be taken when designing a new remedy, conducting a pilot test, or updating an existing remedy based on new information or changes in science and technology. For pump-and-treat, process and parameters such as well placement, extraction rates, pumping duration, aboveground treatments (activated carbon/air striping) can also be sustainably designed. For example, well placements should consider land reuse plans, local zoning, maintenance and monitoring of any engineering and institutional controls. Pumps, blowers and heaters should not be oversized, and pulsed pumping schemes should be adopted when necessary.

The BMPs introduced during construction of pump-and-treat can continue during remedy operation. Sustainable practices can encompass the use of clean fuels and renewable energy sources for vehicles and equipment, retrofitting diesel machinery and vehicles for improved emission controls, reusing construction and routine operational materials, reclaiming demolition or processing waste, and installing maximum controls for stormwater runoff. Sustainable constructions for pump-and-treat also include well placement compatible with reuse and zoning, green chemicals and materials, storm water discharge control, green structure and housing for aboveground treatment train (EPA, 2009b).

A typical pump-and-treat system during the operation stage constitutes 39% labor, 23.5% utilities, 16% materials, 13% chemical analysis, and 8.5% disposal cost, which are all subjective to the deployment of sustainable practices such as renewable energy, green acquisition, recycled or bio-based (e.g., surfactants) materials. Renewable energy for pumps, blowers, and heaters have been used in various Superfund sites in the U.S., including solar energy through photovoltaics (PV) direct or indirect heating and lighting systems, or concentrating solar power; wind energy as an alternative in coastal areas or at high altitudes common to many mining sites. A wind speed of 9 mph (>13 mph for a wind farm) is sufficient for groundwater pumping. Renewable energy systems can operate independently or tie to the existing utility power grid.

**Future perspectives and concluding remarks**

The field of sustainable remediation is still new and growing rapidly in the recent years. As can be witnessed by increased numbers of published guidelines and case studies, the concept of sustainable remediation is generally encouraged by all stakeholders. However, there is a clear need to strengthen the regulatory enforcement, corporate-wide supporting policy and economic incentives to maximize sustainability incorporation into the current soil and groundwater remediation strategies. There are urgent needs for a refined LCA methodology, improved LCA data quality, more case studies toward the development of a generic model, and streamlined data collection for full LCA calculation. More importantly, key environmental impact attributes of remediation activities should be identified to establish the modular backbone of the sustainable technologies. Some of these require the constant sustainable thinking such as green acquisition, recycle-reuse and waste minimization, whereas other require the capital investment of BMPs as well as technological advances such as the use of renewable energy, passive sampling and automatic monitoring for minimal environmental footprints.

Central to the sustainability evaluation and incorporation is perhaps the development of a simple index system prior to a full LCA analysis. This simple index system should incorporate the core “sustainability components” to be meaningful to remediation practitioners. Having been used in other related fields,
sustainability index measures the sustainability of various countries, regions and corporations. The proposed Remediation Sustainability Index (Figure 2) can be developed according to six core elements of green remediation. The index can be calculated from the values of these indicator parameters based on unit contaminant mass removal or restored volume of groundwater. This simple sustainability index can be used as a convenient measure in remediation assessment, basis for providing economic insensitive, and certification program in addition to regulatory provisions. The simplified Remediation Sustainability Index can also be used as a screening tool for sustainability analysis prior to a full LCA. Representative indicators and their weighting under each core sustainability element in Figure 2 are the subject of further research.

The rationale for the proposed RSI is in line with the tiered sustainability evaluation approach as described by Holland et al. (2011). The Tier 1, Tier 2, and Tier 3 evaluations correspond to a qualitative (checklists and rating system), semi-quantitative (spreadsheet-based), and in-depth quantitative life-cycle analysis of the remediation activities. Diamond et al. (1999) in their seminal work proposed the similar life-cycle framework that includes a qualitative life-cycle management (LCM) followed by a more rigorous quantitative LCA to address burdens associated with contaminated sites and remediation activities. The RSI is different to some extent in that it is quantitative, but it represents the major sustainability attributes. The RSI should not just consider the carbon footprint (greenhouse gas accountings), it should reflect the true overall environmental sustainability (Laurent et al., 2012).

Figure 2: A proposed Remediation Sustainability Index (RSI) that consider the six core elements of green remediation

Regardless of the specific sustainability measure to be employed, it is anticipated that sustainability will be included in the approval of Remedial Action Plans in the future in the U.S. and other countries. Cautions should be exercised that the concept of sustainable remediation will not be misused or misguided. If done correctly, sustainable remediation will not and should not be perceived as the lower cost or less invasive remediation alternative to the traditional energy-intensive remediation techniques. Corporates responsible for cleaning up contaminated soil and groundwater will receive credits and an improved image due to the incorporation of sustainable practice.
References


