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Life-Cycle Assessment

LIFE-CYCLE FRAMEWORK FOR ASSESSMENT OF SITE REMEDIATION OPTIONS: METHOD AND GENERIC SURVEY

MIRIAM L. DIAMOND,*† CYNTHIA A. PAGE,† MONICA CAMPBELL,‡ STEPHEN MCKENNA,§ and RONALD LALL‖
†Department of Geography, University of Toronto, Ontario M5S 3G3, Canada
‡Toronto Public Health, North York Civic Centre, 5100 Yonge Street, North York, Ontario M2N 5V7, Canada
§Community and Neighbourhood Services, Toronto Public Health, City of Toronto, 277 Victoria Street, Toronto, Ontario M5B 1W1, Canada
‖R. Addison Lall and Associates, 3-91 Helendale Avenue, Toronto, Ontario M4R 1C6, Canada

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Abstract—To address burdens associated with contaminated sites and issuing from remediation activities, a life-cycle framework (LCF) was developed, including an approach based on life-cycle management (LCM) and an adaptation of life-cycle assessment (LCA). Intended for application to a wide range of remediation options, the objective of the LCF is to broaden consideration of potential impacts beyond the contaminated site and over a prolonged time frame. The LCM approach is a qualitative method for investigating remediation activities from a life-cycle perspective. This adaptation of the more rigorous, quantitative LCA method has involved specifying appropriate life-cycle stages, a long-term time horizon, a spatial boundary encompassing the contaminated site and other affected locations, a process boundary containing the contaminated soil, and an impact assessment method that considers site- and process-related metrics. To assess the suitability of LCM as a decision-making tool, six generic site remediation options were investigated: no action, encapsulation, excavation and disposal, vapor extraction, in situ bioremediation, and soil washing. The analysis exemplified tradeoffs between the streamlined LCM, and comprehensive, quantitative LCA approaches, and highlighted potential environmental and human health impacts arising from the six technologies investigated.

Keywords—Life-cycle assessment Life-cycle management Site remediation Contaminated soil Contaminated groundwater

INTRODUCTION

Life-cycle assessment's (LCA's) conceptual basis, often termed life-cycle thinking, involves analyzing and minimizing burdens associated with a product, service, or activity over its life cycle. The LCA offers a systematic method for evaluating product-based systems, traditionally in the manufacturing and processing sectors [1–5]. Taking advantage of the life-cycle thinking associated with LCA, while simplifying the method, life-cycle management (LCM) has recently evolved as a systematic approach to conceptualize and structure environmental activities, improve strategic decision making, and often to associate economic efficiency with environmental improvement [6,7].

Although LCM and LCA approaches have been typically used for product-based systems, these approaches can be modified for new sectors where systematic consideration of environmental and human health burdens over the life cycle of an activity is required. This paper discusses a new application of LCM and LCA to contaminated site remediation activities. These activities, although directed toward minimizing short- and long-term risks posed by contaminants on-site, have inherent burdens that differ according to the technology. In other words, remediation itself entails impacts. Impacts associated with all options merit consideration so that the ultimate goal of minimizing direct exposure to, and movement of, contaminants is achieved. Presently, government and corporate policies that are directed toward protecting public and ecological health by minimizing liability and risks at contaminated sites focus their attention on the site per se, and typically do not consider total risk or environmental effects in a broader geographic and temporal context. Often the choice of remediation options is predominated by financial and/or technical considerations, rather than environmental or health protection.

To fully protect public and ecological health, we should consider whether remediation activities might clean up contaminated sites and reduce risk in the immediate geographic location, while increasing risk at a larger scale and over a longer time. Examining site remediation activities using life-cycle thinking allows for a systematic review of impacts beyond those immediately associated with the contaminated site and, therefore, promotes consideration of potentially wider impacts.

The goal of this research was to develop a life-cycle based approach, which we termed life-cycle framework (LCF), to examine the broader environmental and human health implications associated with soil and groundwater remediation. This paper presents the LCF that includes descriptions of LCM and the adaptation of LCA to site remediation options.

An additional purpose of this paper was to illustrate and assess the LCM through application to six commonly used site remediation options. The analysis is general, rather than site-specific, with the aim of identifying the main environmental and health concerns associated with each method. The options were compared qualitatively based on potential impacts, followed by a discussion of the analysis.

As reported in a second paper [8], we conducted a detailed, quantitative assessment of an excavation and off-site disposal scenario to illustrate and examine the adapted LCA method, by using data from a completed remediation project

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* To whom correspondence may be addressed (diamond@geog.utoronto.ca).

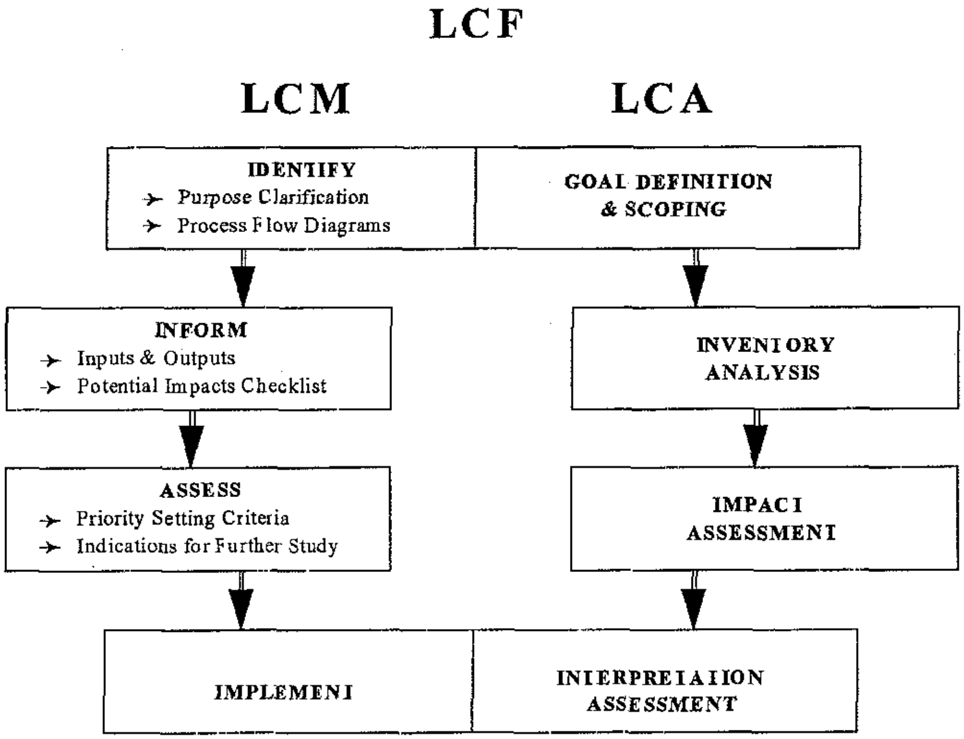

Fig 1 Components of the life-cycle framework for assessment of contaminated site remediation options

LCF: OVERVIEW

The LCF was developed specifically for application to contaminated soil and groundwater remediation options To be of general use, the LCF must accommodate a wide range of remediation options, varying from technologically complex ex situ approaches, to in situ biotechnology, risk management approaches, and no action To ensure its general applicability, the LCF offers two approaches: the simpler, qualitative LCM; and the detailed, quantitative LCA (Fig 1)

The LCM approach was developed in response to requests from site remediation practitioners for a simple method to examine remediation options from a life-cycle perspective and derives from existing LCM concepts [6,7] The LCM method is used for increasing awareness of life-cycle related issues, identifying potential impacts related to a remedial activity, or investigating implications of resource use We modified the existing LCA method [1–5] to accommodate contaminated site remediation activities. The LCA is useful for more detailed investigation beyond LCM where, for example, quantitative information on resource use or information on potential impacts is required

The LCF has two applications, the first for design, and the second for analysis of site remediation activities, either completed or underway Using the LCF for design involves choosing the optimal remediation option to minimize environmental and human health burdens The design may consider the types of raw materials used, energy and natural resource use, transportation issues, waste management options, and long-term impacts of postremediation activities A design application requires the use of generic data, models, or estimates of burdens rather than site-specific information, and thus can be used prospectively The amount of information required for decision making depends largely on the goal of the study

When using the LCF for analysis, a single site or numerous related sites (i.e , contaminated site remediation case studies) may be examined prospectively or retrospectively For example, the focus of the analysis may be to identify opportunities for decreasing environmental impacts or increasing awareness of the impacts associated with a particular remediation approach The LCF for analysis may also be used to provide insight into a current policy focus by prioritizing areas of improvement or clarifying inconsistencies, such as protecting the contaminated site in deference to the recipient of generated waste This method will not provide absolute statements of site-specific impacts but rather, LCF provides insight into potential impacts or burdens associated with specific activities that can be used to guide decisions for on-site cleanup activities or policy

LCM: METHOD FOR CONTAMINATED SITES

The LCM for investigating contaminated site remediation activities consists of four components: identify, inform, assess, and implement (Fig. 1), as described below.

Identify

Identify involves specifying or clarifying the purpose of the study, and describing the remedial system through process flow diagrams. The purpose of the study is described at the outset to help maintain focus and determine the extent of information or assessment required.

Questions to consider Application—will the LCM be used for analysis (e g , case study) or to design a remedial approach? Assessment goals—What are the main goals: to better understand the existing system, to determine opportunities for improving the existing system, to compare remedial systems and their potential impacts, or to select a remediation option prospectively? End users—who is (are) the audience(s) for this study? Will the assessment be used within a private company

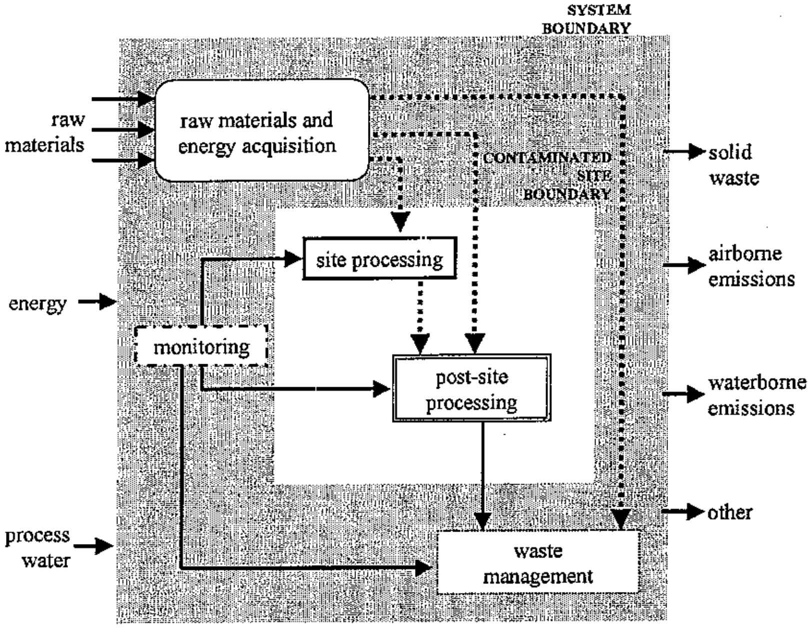

Fig 2 Flow diagram depicting the relationship between site remediation life-cycle stages and inventory items

or publicly? (This choice influences the degree of accountability, whether open to review, level of transparency, and so on.) Bounding—what are the temporal, geographic, and process boundaries of the remediation option option or activity? What processes are secondary or will be neglected?

The remediation option is next described by compartmentalizing all activities into life-cycle stages, and subsequently into unit processes, in order to outline all activities over the entire life cycle. Life-cycle stages, defined below, are raw materials and energy acquisition, site processing, and post-site processing. Life-cycle substages, which may be associated with any life-cycle stage(s), are transportation and distribution, waste management, and monitoring Raw materials and energy acquisition includes activities surrounding the acquisition of raw materials (e g , primary or secondary). Examples of raw materials include those used for capping or barrier walls for encapsulation, nutrients and soil amendments for bioremediation, and clean backfill used in several options Site processing involves the actual treatment of the contaminated soil and groundwater and is considered complete when the contaminated soil and groundwater have been treated or exposed to a remediation option, that is, contaminant concentrations may not necessarily be changed, as in no action or encapsulation. Post-site processing activities occur after the main activities have ceased, but still fall within the overall life-cycle span (e g , activities to maintain site security, upgrading of capping or barrier walls, collection of leachate, or migration control)

The life-cycle substage of transportation and distribution involves changing the location of the soil, groundwater, and materials used as inputs (e.g., reagents, clean fill) and outputs (e g , waste concentrates) Transportation includes moving materials or energy, whereas distribution encompasses all nontransportation activities that facilitate the transfer of the soil, groundwater, and other materials (e g , stockpiling, warehousing). Waste management involves techniques and/or emission control systems to treat, handle, or contain a waste generated from remediation activities, before its release into the environment. Waste is considered an output, with no market value or intrinsic use, discharged into the environment through air, water, and/or land [1] and may be released under routine and accidental conditions. Important considerations include the categories of waste (e g , nonhazardous, hazardous) and the receiving medium Monitoring involves the surveying and tracking of emissions from all activities at all locations within the geographic boundary, not including measures for the waste management activity of emission control.

At times, the distinction between stages may not be clear, for example, whether an activity such as groundwater treatment falls under waste treatment or site processing Determining the actual category is not critical, only that all possibilities are included and reported

Once the life-cycle stages are determined, the major unit processes within each life-cycle stage are identified and the overall process flow diagram is constructed Figure 2 gives a simplified flow diagram with the life-cycle stages described above

The remediation option life span continues beyond completion of site processing, to encompass all activities associated with remediation The life span must be long enough to account for long-term impacts, such as activities associated with partially decontaminated sites or waste management

Inform

Inform involves determining inputs and outputs (i.e., inventory) based on the process flow charts, and investigating the associated potential impacts Depending on the purpose of the study, the inventory information may be qualitative or quantitative (e g., measurements, estimates or averaged values, or nontraditional items) Inputs include raw materials, process water, and energy. Outputs encompass airborne emissions, waterborne emissions, solid waste, heat discharge, and treated soil Nontraditional items are site quality (e.g., soil quality, contaminant levels), information on land use and physical ecosystem degradation, and other disturbances (e g , noise, odor, vibration). In addition, appropriate measures (e g , area) or information (e g , location of valuable habitat, impervious surfaces, land fragmentation, land stagnation) should be gathered. A compilation tool is often useful to systematically record inventory information [1,9]

A raw materials or emissions database appropriate for site remediation activities is not available currently. Therefore, using LCM for design may require obtaining information from contractors, suppliers, or consultants involved directly with site remediation If considering a case study, information may be derived from many sources, however, the type and extent of data required for a life-cycle inventory are not routinely gathered or available (e.g., fugitive emissions are difficult to determine and may require estimation).

The next step involves identifying the inventory items, or groups of items, that are stressors and linking them with potential environmental impacts Stressors are physical, chemical, or biological conditions or entities that can induce positive or negative impacts on the environment, humans, or resources [1] Each stressor, or group of stressors, is associated with one or more potential impacts These impacts represent a wide range of generic, rather than site-specific concerns, and thus are not comparable to, or intended as, risk assessment that is widely used in the site assessment, remediation, and management arenas (e.g., to establish clean-up levels) [10,11]

The stressors and their potential impacts are grouped in three categories: pollution, which relates to all types of emissions to the environment; depletion, which includes inputs that are extracted from the environment; and disturbance, which reflects human social impacts and structural changes to the environment [12]. For land issues, stressors and potential impacts are classified under disturbances, and include physical ecosystem degradation (e g , habitat fragmentation) Solid waste and associated land consumption impacts, however, are considered under depletion since they relate to removing land for "useful" purposes such as habitat

Applying LCM at its simplest level involves identifying potential impacts associated with all stages of the remediation option under consideration, using a potential impacts checklist. The checklist identifies and permits each assessor to rank the level of concern (e g , no or low, moderate, high) linked to stressors from inventory items, thereby ensuring that potential impacts associated with any life-cycle stage are considered. We have suggested ranking stressors according to level of concern rather than amounts, because the former is applicable to all stressors and avoids distortions when dealing with chemical and nonchemical contaminants of varying potency [13]

In this study, members of the investigation team independently ranked the concern levels for each item of the six technology types. Group discussion led to refining the final ranking for each item, thereby minimizing interrater discrepancies. Although the rating process is subjective, bias is minimized by the multiple appraisers working from inventory data towards consensus. This approach is derived from methods on conducting systematic reviews [14] that require two or more appraisers to independently apply a quality assessment tool to determine the quality of a specific scientific study. The level of interrater agreement is noted, and consensus is reached on the final subjective rating.

Assess

Assessing the results and considering future study depends on the study's purpose. To determine the necessity of future work on an inventory item or process, priority-setting criteria can be inferred from the levels of concern in the potential impacts checklist, in conjunction with the following decision points and related questions

Indications for further study—Questions to consider. Consumption levels—how much of the inventory item is used? The less is best principle may apply Toxicity levels—how toxic, persistent, or bioaccumulative is the inventory item? How much of the inventory item is used or emitted in the activity? Liability—is the inventory item regulated (e.g., deemed hazardous)? Do emissions of the item exceed regulated or suggested levels? Environmental sensitivity—is the inventory item considered environmentally sensitive? If a disturbance, is it in an environmentally sensitive or valuable area? Is a sensitive species, population, or community disturbed? How geographically dispersed or long term are the effects?

Associated costs or opportunities. What are the costs associated with attempting to alter costs or opportunities (e.g., decrease amount produced) versus not changing the inventory item?

Implement

Implement involves acting on the conclusions of the study and may be done in conjunction with any other LCM stage. Once the decision points have been considered, key areas for improvement are identified. At the simplest level, the LCM approach provides increased awareness through life-cycle thinking and a cursory investigation into potential impacts associated with a remediation technology. At a more complex level, LCM helps to identify key areas for improvement that are consistent with the purpose of the study and the priorities of the user.

LCA: METHOD FOR CONTAMINATED SITES

The LCA approach provides systematic, rigorous, and detailed assessment of site remediation options The following discussion details the process of site remediation and modifications necessary when applying LCA.

Boundaries

The quality of a life-cycle inventory, and the subsequent life-cycle impact assessment (LCIA), depends on an accurate description of the system and, as with all LCAs, the boundaries drawn. Establishing system, temporal, and geographic boundaries is critical to the overall objective of expanding environmental and health concerns beyond the boundary of the contaminated site.

The temporal boundary must encompass the time taken for all remediation activities and over which concerns arise The temporal boundary also influences the age of data used at the inventory stage We propose a time horizon of approximately 25 years starting with remediation, not when the contamination occurred. This time horizon is intended to capture longer term effects that could arise from the no-action or limited-containment scenarios, or storage of contaminated waste The extended time frame is also necessary so that the LCA does not prejudice options that may have high impacts over a short time (e.g., soil washing) relative to those having lower impacts over a longer time (e.g., in situ bioremediation). Practically, time is treated by estimating inventory items over the time horizon (e.g., projecting the energy required to maintain a waste disposal facility for 25 years).

The system boundary includes all operations involved in remediating the contaminated soil and groundwater, and separates the system from the surrounding environment Including soil within the system boundary is debatable. For options involving soil excavation followed by treatment (e g., soil washing), soil and groundwater might be considered outside the system However, if the treatment option leaves the soil structure intact (e.g., in situ bioremediation, soil venting), then the soil may be regarded as inside the system boundary We propose that, because the soil is an integral component of site remediation processes, it should be included within the system boundary Similarly, Cowell and Clift [15] recommended that soil be included within the boundary of their LCA of farming and food production systems, and emphasized that changes in soil quality should form part of the inventory analysis Likewise, we propose that including soil within the system requires consideration of site quality that is addressed through impact assessment using a suite of site quality metrics in addition to those pertaining to process-related activities.

The geographic boundary is central to the original intent of using an LCA approach for site remediation. The boundary encompasses activities at and beyond the contaminated site itself, thereby allowing consideration of geographic shifts of burden from one site to another For example, excavation and disposal involves relocating contaminated soil to other area(s) and clean fill must be transported from yet another location

Process description

The remedial process under consideration can be illustrated by a process flow diagram that first identifies the main process flow, and then adds ancillary material flows Process descriptions vary widely because of the nature of remediation options, which may range from no-action options to complex, multistage remedial technologies

The functional unit, or normalizing factor, is a performance measure necessary for comparative studies that should reflect the total benefit or service provided by the system, the product lifetime, the study objectives, and the equality of resultant products (e g , quality and quantity) [4]. For site remediation, the primary process is treating contaminated groundwater and soil, and the benefit or service provided is the remediation of a contaminated site The function provided is the remediation of the site that, depending on the technology used, can result in a wide range of final on-site contaminant concentrations and can vary in effectiveness or permanence of remediation. For example, a technology may immobilize metals but not treat organic contaminants, whereas another contains rather than treats contaminants

A functional unit that conveys equal use utility would be best; however, it is difficult to develop such a unit given the wide variety of remediation outcomes and dependence of land use potential on social and/or economic factors (e g., land value depends on location, market conditions, and so on) Although a single best functional unit is unclear, we suggest that the functional unit should relate to the production of an equivalent amount of treated soil and groundwater; we consider site quality separately. The amount of treated soil, expressed as a volume or mass, is most readily quantified when the site is initially characterized. More accurate estimates of final volume or mass would be obtained for options involving soil excavation; however, these values are likely to be uncertain for in situ treatment or containment options, or for the no-action scenario.

Because mass or volume of cleaned soil do not address the extent of clean up, contaminant immobilization, nor the quality of the treated soil, site-related impact metrics are suggested to address the nature of clean up. These metrics include the concentrations of contaminants in soil and groundwater, pH, porosity, particle size distribution, organic matter content, nutrient content, and ion exchange capacity Other metrics that reflect the final nature of the site should also be included

Data issues

The results of any LCA are contingent on the data used. As outlined by SETAC [9], many data types and sources exist and several data categories can be considered When LCA is used for the analysis of remediation options, case studies are usually considered and, consequently, data are obtained from primary sources. The data are facility-specific industry or consultants' reports collected over the duration of the actual site remediation, and are often proprietary Because they are specific to particular remediation cases, the data are not representative of site remediation processes in general, and deviations or variations are not averaged Data from government documents and environmental assessments typically lack sufficient detail Because consultants, suppliers, contractors, and technology vendors offer judgmental data, caution must be exercised when using these sources. Ideally, data should come from an unbiased source and be subject to peer review With LCA for design, problems arise in accessing generic data Models for predicting life-cycle inventory data do not exist; likewise, generic databases specifically for site remediation are not yet available.

Life-cycle stages

The intention of the LCA convention of breaking down a process into life-cycle stages is to avoid duplication or omission of any activities The life-cycle stages for LCA applied to site remediation are discussed and illustrated in Figure 2. Although some stages are not encountered for all remediation options, the stages accommodate most scenarios

Impact assessment

The LCIA qualitatively and quantitatively classifies, characterizes, and evaluates potential impacts to ecosystems, human health, and natural resources [16] Similarly to LCM, the impact assessment component of LCA requires identification of stressors and potential impacts that are classified within the three impact categories Unlike LCM, LCA involves translating inventory items into relevant indicators of potential environmental and health impacts using models or assessment approaches.

We suggest two sets of metrics to gauge if remediation mitigates potential impacts due to contaminated soil and groundwater. Process-related impacts are derived from the inventory and relate to activities such as transportation or leachate collection, whereas site-related impacts relate to site quality

Assessing ecological and human toxicity as part of process- and site-related impacts is essential for the analysis because the objective of site remediation is to minimize these effects Because of the generic nature of the analysis, the assessment estimates potential toxicity effects, but not at the site-specific level of risk assessment For process-related chemical emissions (in contrast to soil and groundwater contaminants), we suggest following the approaches detailed by Guinée and Heijungs [17] and Jia et al. [18] that use a multimedia Mackay model (e.g., level III fugacity model of Mackay et al. [19]) coupled with toxicity data that are commonly used in risk assessment (e g , tolerable daily intake [TDI]) Fugacity is preferred for chemicals that have a measurable vapor pressure, whereas aquivalence must be used for chemicals lacking a measurable vapor pressure, such as metals [20], and the multispecies formulation should be used for chemicals that exist as multiple, interconverting species, such as mercury [21]. Using a multimedia model coupled with toxicologic benchmarks accounts for differences in the mobility, tendency to bioaccumulate, and toxicity of persistent chemicals. The fate of short-lived, reactive chemicals must be estimated using dispersion or point-of-impingement models

The multimedia approach suggested above is not well suited to characterizing the effects of contaminants remaining in soil and groundwater following remediation because multimedia fate is not necessarily of primary importance. To address site effects, we suggest using a model that specifically treats the persistence and mobility of soil and groundwater contaminants, and links these contaminant concentrations to toxicity effects for human and nonhuman receptors.

In addition to assessing the potential effects of contaminants left on-site and characterizing soil quality, a metric is necessary for expressing land use, or conversely, land rendered unusable or hazardous because of contamination. By land use we refer to the potential use of the land for habitat to support biodiversity, or for agriculture, residential, or industrial purposes. Land use relates to the site itself, as well as sites used for soil disposal and for obtaining clean fill Solid waste burden (SWB) is a volumetric indicator used to reflect the space occupied by waste and reflects landfill burdens, thereby circumventing spatial (e g , area) issues. Alternately, a simple metric reflecting useable land area may be employed; however, the use of the land must be specified because not all uses are equally productive or desirable (e g , use for habitat versus industrial development) Obviously, difficulties arise when attempting to use one metric to reflect all facets of land use We therefore propose using, at the least, the SWB metric coupled with the useable land area to reflect land issues

LCM ANALYSIS OF SIX GENERIC REMEDIATION OPTIONS

The following analysis of six generic remediation options illustrates the use and types of results obtained from an LCM approach. The analysis is presented according to the LCM stages of identify, inform, and assess The options considered are no action, encapsulation, excavation and disposal, vapor extraction, in situ bioremediation, and soil washing. Process descriptions are derived from previous research of on-site remediation technologies [22] and additional references as noted

Identify

The purpose of this illustration is to improve our understanding of the potential environmental burdens of six generic remediation options; consequently, a qualitative study is appropriate The end users of this work include those interested in the environmental implications of remediation activities such as policy makers, large land holders, and consultants The temporal boundary is long term and the geographic boundary includes all sites affected (e g , hazardous and nonhazardous waste disposal facilities, borrow pits for clean fill) The process boundaries encompass all major processes or activities We neglect secondary processes (e g , production of reagents used in soil washing) for the sake of simplification.

The major activities involved with each generic remediation option are described below and presented in process flow diagrams (Fig. 3) By convention, energy acquisition is considered, but not included in the descriptions and diagrams.

No action involves leaving contaminants on-site without intervention (Fig. 3a). The contaminants will distribute into air, water, soil, and sediment on- and off-site according to their physicochemical properties and environmental characteristics, and may degrade or be transformed [23,24].

Encapsulation isolates the contaminated soil and groundwater by means of walls or panels and surface caps. Encapsulation typically involves (Fig. 3b) excavating a trench around the contaminated area until an impermeable subsurface layer is reached; transporting materials and equipment for walls and cap, and equipment for excavation; producing impermeable walls/panels; and filling the trench with these impermeable walls/panels (e g , clay, clay slurry, concrete, sheet piles) [25,26]. If an impermeable subsurface layer is not found at a reasonable depth, an impermeable base is constructed Material(s) for surface caps are produced and then applied (e.g., impermeable soils, soil admixtures, synthetics, clay) [25] Finally, caps and walls are subject to long-term monitoring and maintenance

Excavation and off-site disposal of contaminated soil involves removing contaminants from the site for disposal in a landfill site(s) and then backfilling the excavation Typical main activities (Fig 3c) include excavation of contaminated soil, dust mitigation procedures, pumping and treating groundwater and process water [27], transporting soil and water treatment sludge off-site [28], disposal of soil and sludge in a hazardous and/or nonhazardous landfill site; and discharge of treated water to sewers Clean soil for backfill is excavated, transported to the site, and placed in the excavation pit. The landfills are monitored and maintained over the long term [29]

In situ engineered bioremediation involves microbial degradation or transformation of contaminants that may be enhanced by adding, for example, oxygen, nutrients, acids or bases to control pH, surfactants to mobilize trapped contaminants, and organic cosubstrates [30,31] Main activities (Fig 3d) include drilling a network of injection and extraction wells for hydraulic control of contaminated groundwater; recovering free product present as a distinct nonaqueous phase; treating and returning groundwater (hydraulic control); capturing volatile organic compounds (VOCs) from wells; and pumping groundwater to increase flow and movement of nutrients, oxygen, and compounds for enhancing degradation. Indigenous organisms may be removed from the site for selection, enrichment, and reintroduction, or they can be augmented with genetically engineered organisms [32]. The system is monitored for clean-up progress.

Soil washing is an ex situ soil treatment process capable of separating a wide variety of contaminants into a concentrate of soil fines, leaving a clean coarse fraction [33,34] The major activities (Fig 3e) are soil excavation, transporting excavated soil to pretreatment and soil-washing facilities, soil preparation (e g , breaking, crushing, blending, or rejecting oversized material), soil washing (soil is mixed, washed, and rinsed with water and/or solvents or reagents), and soil recovery in two fractions (a clean coarse fraction and the contaminated silt and clay fraction) The extracting agents and treatment chemicals are produced and transported to the soil washing facility The contaminated process liquid is treated, resulting in liquid treatment residuals (sludge) and contaminated fines that are managed through disposal as landfill, and process water that is

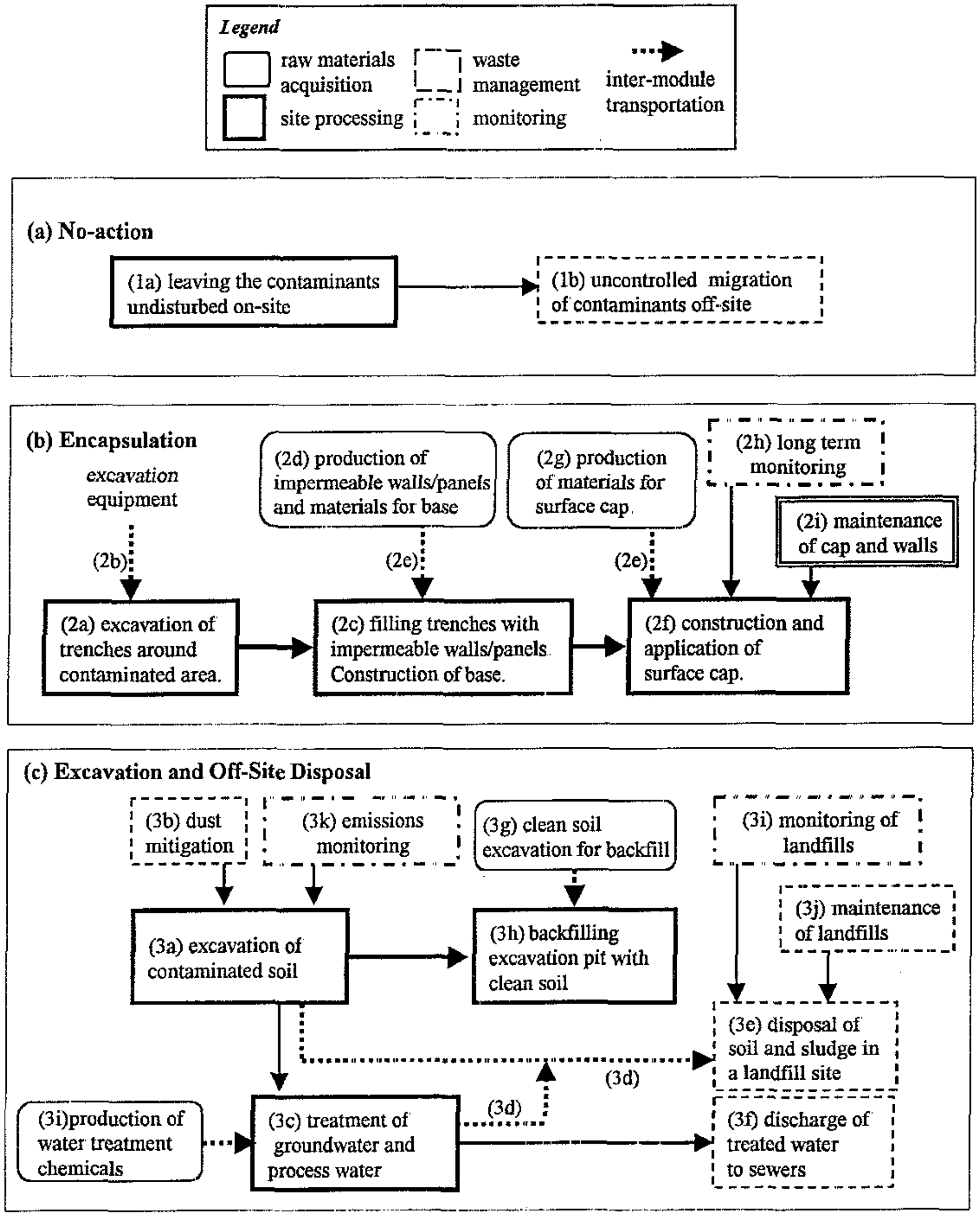

Fig. 3. Flow charts for generic remediation options: (a) no action; (b) encapsulation; (c) excavation and off-site disposal; (d) in situ bioremediation; (e) soil washing; and (f) vapor extraction

discharged to surface waters. The washed coarse fraction may be returned to the site as clean backfill that requires soil amendments to improve quality. On-site monitoring occurs for fugitive dust and volatile emissions, and long-term maintenance and monitoring of landfills is necessary

Vapor extraction (Fig. 3f) involves applying a negative pressure to the soil via aboveground vacuum pumps connected by airtight piping to extraction wells [35]. The negative pressure removes air, moisture, and the vapor phase of VOCs and semivolatile chemicals from the soil surrounding the extraction wells. Clean heated air may be pumped into the soil through injection wells [27], or allowed to flow through inlet wells [36]. The air and water are separated, and the contaminated air is treated before venting using, for example, activated carbon adsorption (considered here), or a variety of options that may include thermal destruction, catalytic oxidation, condensation, biological degradation, or ultraviolet oxidation

Inform

Typical inventory items for each remediation option are listed in Table 1 with numerical reference to the activities described above and presented in Figure 3. The inventory items, or groups of items, are then linked qualitatively with potential environmental and human health impacts using a

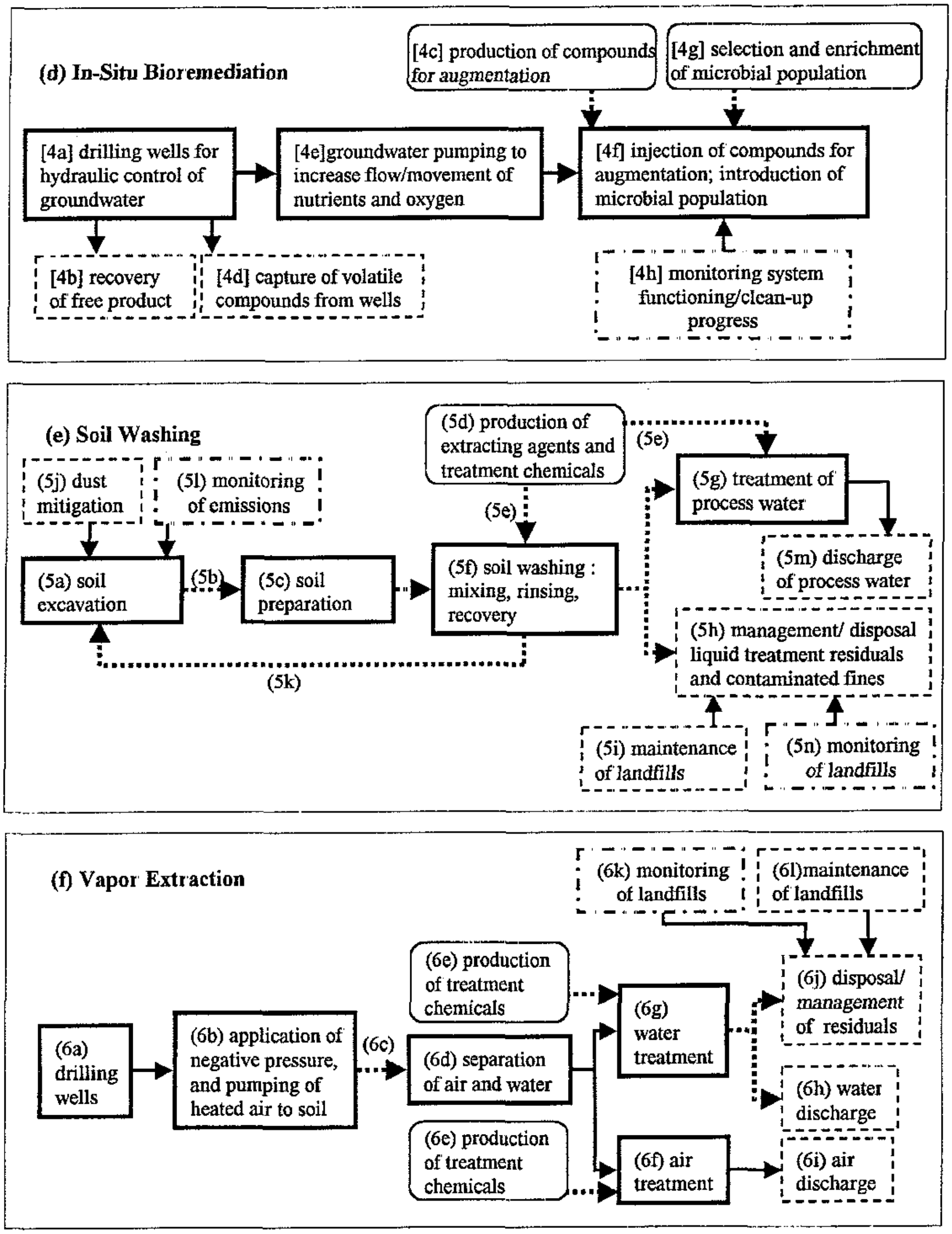

Fig 3 Continued

potential impacts checklist (Table 2) to highlight potential areas of concern

Three levels of concern reflect the severity of potential impacts: no or low concern, moderate concern, and high concern [13]. We have developed qualitative criteria to guide the ranking process For all stressors, no or low concern refers to a lack of, or negligible presence or concern regarding the stressor in question. Ranks of moderate or high concern are assigned based on the following criteria: discharge amount or emission rate, time frame of disturbance, reversibility of disturbance, ability to control or contain the process or emission, and ability to monitor or verify the process or emission (i.e., uncertainty). Further guidance for ranking is given below, according to the main stressor categories The ranking presented in Table 2 reflects our current interpretation of the inventory information, and reflects the judgment of a multidisciplinary team

Pollution stressors can be ranked according to amounts emitted, with attention given to potency. For process-related impacts, regional concerns can be considered when ranking acid emissions, air pollutants and photochemical smog, nutrients, process water quality, and toxic air contaminants, based

Table 1. Typical inputs, outputs, and other information for remediation options (numbers and letters following the inputs, outputs, and other information refers to those in Fig. 3)

Inputs	Outputs	Other information
No action		
None	Air emissions	Nonremediation of land (1a)
	Volatile contaminant emissions (1b)	Contaminants remain in place (1a)
	Water emissions	Negative social perception of site (1a)
	Migration of contaminants in groundwater (1b)	
Encapsulation		
Material resources	Air emissions	Diversion of groundwater (2a, c)
Jetting fluids (2a)	Dust (2a)	Alteration of groundwater recharge (2f)
Grouting (2c)	Volatile contaminant emissions (2a)	Noise, vibration (2a)
Panels: steel panels (2c, d)	Transportation-related emissions (2b)	Space needed for construction of some walls (2c)
Membrane walls (2c, d)	Water emissions	Possible contaminant leakage, or breaches in wall integrity (2h, i)
Surface cap layers (2f)	Contaminated cutting fluid (2a)	Site use limited to surface (2f)
Energy resources		Contaminants remain in place (2c, f)
Diesel (2a, b, c, d, e, f, g)		
Excavation and disposal		
Material resources	Air emissions	Noise (3a, d, h)
Wastewater treatment chemicals (31)	Dust (3a, e, g)	Space consumption at landfill (3e, j)
Clean backfill (3g)	Volatile contaminant emissions (3a, e)	Off-site excavation (3g)
Energy resources	Transportation-related emissions (3a, d, g, h)	
Diesel (3a, c, d, g, h, l)	Solid wastes	
	Hazardous/nonhazardous soil and sludge (3e)	
	Water emissions	
	Treated process water, groundwater (3f)	
Bioremediation		
Material resources	Air emissions	Noise (4a)
Compounds for augmentation (4c)	Dust (4a)	Alteration of indigenous microbial population (4f, g)
Noncontaminated water (4f)	Volatile contaminant emissions (4a, b, d)	Alteration of natural groundwater flow (4a, e)
Nutrients (4f)		
Electron acceptors (4f)		
Acid/base for pH control (4f)		
Microbial population (4g, h)		
Energy resources		
Diesel, other (4a, e, f)		
Soil washing		
Material resources	Air emissions	Noise (5a, b, c, f, j)
Surfactants and chelating agents, other treatment chemicals (5d)	Dust (5a, c)	Alteration of groundwater flow (5a)
Clean soil (if necessary) (5i)	Volatile contaminant emissions (5a, c)	Space consumption at landfill (5h, i)
Energy resources	Transportation-related emissions (5b, e, k)	
Diesel, other (5a, b, c, e, f, g, h, k)	Solid wastes	
	Disposal of fines and water treatment residues (filter cake) (5h)	
	Water emissions	
	Process water (with some treatment chemicals) (5m)	
Vapor extraction		
Material resources	Air emissions	Noise (6a, c)
Treatment chemicals for air (e.g., activated carbon) (6e)	Treated air (6i)	Space consumption at landfill (residuals) (6j)
Treatment chemicals for water (6e)	Solid wastes	Heating effects on soil (6b)
Energy resources	Residuals (6f, g, j)	
Diesel, other (6a, b, c, e, f, g)	Water emissions	
	Treated water (6h)	

Table 2. Potential impacts checklist for remediation options[a]

Stressor categories	Potential impact categories	No action	Encapsulation	Dig & haul	In situ bioremediation	Soil washing	Vapor extraction
		Levels of concern for remediation options					
	Pollution						
● Acid emissions[b]	Acid rain	☐	☐	■	☐	☒	☐
● Greenhouse gases[c]	Global warming	☐	☒	■	☒	☒	☐
● Ozone-depleting substances[d]	Ozone-depletion	☐	☐	☐	☐	☒	☐
● Air pollutants and photochemical smog[e]	Air pollution	☐	☐	■	☐	☒	☐
● Nutrients discharged	Eutrophication	☐	☐	☐	☒	☐	☐
● Process water quality stressors	Stress on aquatic species	☐	☒	☒	☐	☒	☒
● Toxic contaminants and particulates to air	Airborne transport to other media[f]	■	☐	■	☒	■	☒
	Human health impairment[g]	■	☐	☒	☐	☒	☒
◇ Toxic contaminants in surface and ground water[h]	Ecotoxicity impacts	■	■	☐	☒	☐	☒
	Human health impairment[g]	■	☒	☐	☒	☐	☒
◇ Toxic contaminants in soil[h]	Ecotoxicity impacts	■	■	☐	☒	☐	☒
	Human health impairment[g]	■	☒	☐	☒	☐	☒
◇ Chemical soil quality stressors[ij]	Soil quality disturbances	☐	☐	☒	■	■	☐
	Disturbance						
● Heat discharge	Heat damage/dispersion of heat	☐	☐	☐	☒	☐	☒
● Off-site construction, excavation, or land fragmentation	Habitat alteration or destruction	☐	☐	■	☐	☒	☐
◇ Nonremediation of land	Land stagnation	■	■	☐	☐	☐	☐
◇ Compaction, paving, or application of an impervious soil coverage	Effects on soil moisture, aquifer recharge, ecosystem regeneration	☐	■	☐	☐	☐	☐
◇ Aquifer quality stressors	Interrupted drainage, changes in aquifer level, change in stream base flow	☐	■	☒	☒	☒	☐
◇ Nonchemical soil quality stressors[ik]	Soil quality disturbances	☐	☐	☒	☐	■	☐
● Human social stressors[l]	Human social disturbances	☒	☐	☒	☐	☒	☐
	Depletion						
● Fossil fuel use/energy consumption	Primary energy source depletion	☐	☒	■	☐	☒	☒
● Solid waste	Land or space consumption	☐	☐	■	☐	☒	☐
● Water use	Water consumption	☐	☐	☒	☐	☒	☐
● Mineral use	Mineral consumption	☐	☐	☐	☐	☐	☐

[a] ● and ◇ denote process- and site-related stressors, respectively. Levels of concern are no or low (☐), moderate (☒), and high (■).

[b] SO_x, HCl, NO_x, particulates.

[c] CO_2, chlorofluorocarbons (CFCs), methane, methyl chloride.

[d] CFCs, CO, methyl furan, methyl chloride.

[e] Volatile organic compounds (VOCs), semivolatile compounds, PAHs, NO_x, SO_x, particulates.

[f] Ecotoxicity.

[g] Human toxicity.

[h] Migrating or remaining in surface water, groundwater, or soil.

[i] Affecting or changing the original (i.e., preremediation) soil quality.

[j] Nutrient levels, organic content, microbial population, pH.

[k] Porosity, soil particle size.

[l] Noise, dust, odor, vibration, aesthetic value, psychosocial effects.

on knowledge of the receiving environment (e.g., low alkalinity or oligotrophic receiving waters, emissions of smog precursors to nonattainment areas). In contrast, site-specific stressors relate to effects of chemicals remaining on-site, with attendant ecotoxicologic and human toxicologic implications, and the ability for ecosystem regeneration. Thus, options with low removal efficiencies will receive high concern rankings for these stressors. Chemical soil quality stressors (e.g., nutrient levels, organic carbon content, microbial population, and pH) refer to soil changes relative to preremediation conditions.

Disturbance stressors contribute to nonchemical consequences of remediation and related activities. Off-site construction, excavation, and land fragmentation are a high concern if they are unavoidable and affect off-site land use over the long term. No action and encapsulation of land are designated a high or moderate concern if the remediation option renders most or part of the site, respectively, unavailable for new potential uses. Stressors indicating site-specific aquifer quality refer to changes in groundwater quantity that could result from capping, adding barrier walls, or changing aquifer characteristics by replacing native soils with, for example, coarse fill. Nonchemical soil quality stressors (e.g., porosity, soil particle size) are a high concern if the soil composition is changed. Human social stressors include noise, dust, odor, vibration, changes to aesthetic value, and psychosocial effects. Because of the variety of effects, designating a particular level of concern may be difficult.

Depletion stressors refer to the use of resources relative to their stock or flow. Regional specificity may be incorporated in the ranking, such as water use relative to its abundance, or contaminated soil excavate relative to land available for disposal.

Assigning levels of concern can be challenging because of the varied nature of information available for each technology, as noted by Campbell et al. [13]. However, unlike their study, assigning levels of concern is guided by the inventory data that are related to the stressor–potential impact links established in the potential impacts checklist.

Assess

The extent of analysis at this stage depends on the goal of the study, which, for this study, is to investigate generic remediation options to better understand their potential environmental and human health impacts. To address this objective, we highlight significant stressors from the potential impacts checklist.

For the no-action scenario, the stressors of concern are site-related. The contaminants on-site remain untreated; therefore, the land remains stagnant and unavailable for other uses. Because of on-site contaminants and the potential for off-site migration of contaminants via groundwater, soil erosion, and volatilization, important stressors include on- and off-site contaminants in surface water, groundwater, and soil that pose a potential risk to ecosystem and human health.

Encapsulation minimizes contaminant migration and on- and off-site exposure to biota and humans; however, contaminant concentrations on-site are not intentionally reduced. Consequently, the land is partially restricted for other uses (i.e., limited to surface use only) and land stagnation may occur. The addition of a cap and barriers represents a major disturbance to the site and environs (e.g., soil moisture, groundwater level and flow, stream base flow, potential ecosystem regeneration). Because on-site contaminant concentrations are not altered, encapsulation may be associated with on-site toxicity impacts through groundwater and soil.

For excavation and off-site disposal, the main stressors are process-related and occur off-site. Chemical emissions to air from on- and off-site transportation are functions of distance traveled (e.g., to waste disposal site, from backfill source). Transportation thus affects air quality and global warming, as well as energy source depletion (e.g., transportation fuel). Excavation of backfill (i.e., for clean fill) affects land use at the borrow pit. Finally, the disposal of solid waste produced, which may be hazardous and/or nonhazardous, leads to land consumption, and energy and resource consumption that accompanies long-term maintenance and monitoring at the receiving site(s).

Reducing contaminant concentrations by in situ bioremediation can be a long-term enterprise. Thus, significant stressors relate to contaminants remaining on-site or migrating off-site that could contribute to ecosystem and human health impacts. Nutrients injected into the soil to promote contaminant biodegradation may be discharged or leach into surrounding surface waters or groundwater, thereby contributing to eutrophication. Groundwater pumping to remove contaminants and promote oxygen and nutrient exposure may affect aquifer quality. All activities may alter the site's indigenous microbial population (e.g., introduction of genetically engineered microbial population) and soil quality. In some cases this alteration may be positive, such as nutrient addition and soil aeration.

Soil washing treats excavated soil relatively rapidly but with attendant emissions resulting in on- and off-site impacts. Excavation before treatment may result in emissions of VOCs and contaminant-sorbed dust, similarly to that for excavation and disposal. On-site, the process alters soil quality (e.g., nutrient levels, organic content, particle size distribution), which affects land use or ecosystem regeneration. Fossil fuel combustion for transportation and process energy results in off-site chemical emissions to air with attendant impacts, and resource consumption. Because soil washing essentially separates a coarse, clean fraction from the contaminant-sorbed fines, the latter requires disposal leading to land or space consumption. Energy and materials are required for long-term monitoring and/or maintenance at the recipient site. Clean backfill may be required to rehabilitate the site, causing disturbance at the borrow pit and water may be consumed, although process water is often recycled.

As for in situ bioremediation, the more significant stressors for vapor extraction are site-related, involving potential ecosystem and human health impairment associated with contaminants remaining on-site in soil and groundwater during the lengthy remediation process. Solid waste associated with water and air treatment requires disposal, which may contribute to land or space consumption.

Discussion of LCM analysis

The LCM approach illustrated here provides a broad and systematic consideration of potential impacts associated with site remediation options. The intent of LCM is to be inclusive by spanning the life cycle of a remediation option and expanding the analysis beyond the contaminated site itself. Considering a long time frame equalizes or amortizes burdens that may be considerable but occur over a short time period (e.g., soil washing) compared with lower impacts occurring for a prolonged time (e.g., no action, the disposal side of excavation and disposal) By broadening the analysis in these ways, hidden or externalized impacts are identified, potentially changing the desirability of options.

The LCM investigation of the six remediation options has highlighted concerns beyond those deduced from other commonly used methods such as risk assessment Nontreatment options address contaminated sites through either decisions (i.e., no action), management (i.e., encapsulation), or removal of both the soil and contaminants from the site (i e , excavation and disposal) The options have potential impacts on land use possibilities and land consumption. No action and encapsulation limit land use possibilities at the site, whereas excavation and disposal leads to land consumption elsewhere (e g , hazardous landfill facility, backfill source) Furthermore, transportation necessary with the excavation and disposal option can result in impacts to air quality and resource consumption, impacts that are typically neglected Finally, potential ecosystem and human health impacts may occur because of contaminants remaining on-site.

The treatment options considered here reduce contaminant levels through technology. The potential impacts from vapor extraction and in situ bioremediation relate largely to contaminant removal efficiency, which can result in ecosystem and human health impairment For in situ bioremediation and soil washing, on-site aquifer quality may be affected and off-site water quality can be impaired by the discharge of compounds used in the treatment processes Soil washing contributes to diminished off-site land use possibilities because concentrated contaminants must be discarded at a receiving site, although the volume discarded is much less than the original volume of contaminated soil. In addition, resources must be used to maintain the disposal site(s) over the long term.

The LCM approach used to clarify potential impacts is conceptually simple, requires qualitative data, and can be used with relative ease when assessing numerous options Thus, it is flexible and broadly applicable Perhaps the most effective use of the approach is to promote life-cycle thinking, and to methodically investigate and highlight potential, often ignored, or discounted impacts associated with a remediation approach A concern arising when using a simplified approach versus the more rigorous LCA relates to streamlining issues in which unforeseen subtleties may be overlooked or neglected leading to distortions [37] These concerns, which can also pose challenges in a quantitative analysis, can be mitigated by using a consultative process and peer review, as has been done here

The ability to conduct an LCM and more in-depth studies lies in the intensive research and survey of literature required Detailed information is essential for the inform and identify components of LCM, and the quality of the information affects the overall quality of assessment.

Another important concern regarding the LCM approach relates to the use of expert judgment when assigning the various levels of concern in the potential impacts checklist. The assignment relies on the practitioner's expertise to approximate the relative importance of the various stressors for the remediation option(s) based on a qualitative inventory. Bias in the rating process can be minimized by an initial, independent assessment by multiple appraisers and then reaching consensus through discussion. The intent of the checklist is to emphasize a broad range of potential impacts rather than relying on a few criteria.

In addition to environmental and human health impacts, the inclusion of other major considerations such as cost, appropriateness of treatment, community disturbance, or completion time, will ultimately form the ideal framework. As with many evaluation methods, the final outcome depends on those conducting the evaluation, which again argues for multistakeholder involvement and peer review Finally, the LCF approach is not intended to be used in place of risk assessment, which focuses exclusively on toxicity, or other site-specific assessment tools. Rather, the LCF provides insight into a wide range of potential impacts, including those that could occur on a site-specific basis (e g , aquifer quality), and at regional and global scales (e.g., acid rain and global warming, respectively).

CONCLUSIONS

An LCF was developed, consisting of LCM and modified LCA methods, to examine potential environmental and health impacts associated with contaminated site remediation options The LCF may be used to design site remediation options or analyze remediation case studies. From a qualitative perspective, LCM helps to identify and clarify aspects of site remediation that contribute most to the broad environmental burden of remediation and involves the four major steps of identify, inform, assess, and implement The LCA, used for quantitative examination, has been modified by setting the temporal boundary to capture and average impacts occurring over the long and short term, including soil within the process boundary, defining mass or volume of treated soil as the functional unit, redefining life-cycle stages, and establishing two suites of impact assessment metrics (site- and process-related).

Applying the LCM approach to six generic options offers insight into potential impacts beyond those identified in, for example, risk assessment, which estimates toxicity impacts only. This analysis indicated that no action and encapsulation options result in potential impacts related to land use and land consumption, as well as ecosystem and human health impacts, because contaminants remain on-site Excavation and disposal relocates contaminants and, in doing so, results in off-site impacts such as land consumption, and those related to emissions and resource use due to transportation. Potential impacts associated with in situ bioremediation and vapor extraction relate to contaminant removal efficiency and, for the former, changes to aquifer and soil quality In situ bioremediation and soil washing could cause adverse effects through the discharge of process chemicals. For soil washing, along with excavation and disposal, concern exists for potential air quality impairment due to excavation and transportation, and land productivity related to disposing contaminants off-site and obtaining backfill.

The framework facilitates a methodic investigation of activities associated with site remediation, and guides the analysis of potential environmental, human health, and resource depletion impacts The framework allows for the consideration of a wide range of potential impacts by expanding consideration beyond a contaminated site itself, and the temporal boundary of on-site activities Possible uses of the LCF relate to providing an environmental and human health perspective for decision-making; for example, when choosing an option or identifying important stages within an option that contribute to the overall burden. It is anticipated that the ultimate use of this approach will come in rationalizing site remediation activities and policies to minimize overall ecosystem and human health impacts using a broad and holistic analysis

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