Guidance for Performing Footprint Analyses and Life-Cycle Assessments for the Remediation Industry

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The US Sustainable Remediation Forum (SURF) proposes a nine-step process for conducting and documenting a footprint analysis and life-cycle assessment (LCA) for remediation projects. This guidance is designed to assist remediation practitioners in evaluating the impacts resulting from potential remediation activities so that preventable impacts can be mitigated. Each of the nine steps is flexible and scalable to a full range of remediation projects and to the tools used by remediation practitioners for quantifying environmental metrics. Two fictional case studies are presented to demonstrate how the guidance can be implemented for a range of evaluations and tools. Case-study findings show that greater insight into a study is achieved when the nine steps are followed and additional opportunities are provided to minimize remediation project footprints and create improved sustainable remediation solutions. This guidance promotes a consistent and repeatable process in which all pertinent information is provided in a transparent manner to allow stakeholders to comprehend the intricacies and tradeoffs inherent in a footprint analysis or LCA. For these reasons, SURF recommends that this guidance be used when a footprint analysis or LCA is completed for a remediation project. © 2011 Wiley Periodicals, Inc.

INTRODUCTION

The remediation industry has successfully cleaned up thousands of sites contaminated with a variety of pollutants using numerous methods. The beneficial intent of these site cleanups is to remediate contaminated media and reduce risks to human health and the environment to acceptable levels. Historically, the activities conducted during cleanups that can impact the environment have not been completely considered or evaluated. Furthermore, potential impacts to human health and ecosystems beyond those typically addressed in human health and ecological risk assessments have not been considered. Externalities, such as societal costs, have not been included in evaluations as well. If these impacts are taken into consideration, some of the negative impacts from remediation activities may be avoided or reduced. Identifying these potential impacts early in remedial planning enables decision makers to maximize opportunities to reduce negative impacts.

Sustainability is an emerging and evolving concept used with increasing frequency in today's business world. Every day, corporate decision makers grapple with their company's impact on the environment, natural resources, human health, and society—in addition to tackling questions of economics. Sustainability principles involve balancing

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three core aspects: environmental, economic, and social. Life-cycle management is a business approach that can be used to target, organize, analyze, and manage information and activities toward continuous improvement along the life cycle. Life-cycle management is about making life-cycle thinking operational for businesses that are striving toward reducing their footprints and minimizing their environmental and socioeconomic burdens while maximizing economic and social values.

The Sustainable Remediation Forum (SURF) White Paper (US SURF, 2009) identified the need for balanced decision making and also a need for technical guidance to help guide practitioners in understanding and implementing sustainable remediation. The need for guidance to assist remediation practitioners in evaluating the impacts resulting from remediation activities is clear. In this article, SURF proposes a nine-step process for conducting and documenting an environmental assessment of remediation projects. This guidance is designed to assist remediation practitioners in evaluating the environmental and human health impacts resulting from remediation activities so that preventable impacts can be mitigated. The guidance methodology can be applied to economic and social aspects, but here the focus is on the environmental and human health impacts as a first step.

Life-cycle management is about making life-cycle thinking operational for businesses that are striving toward reducing their footprints and minimizing their environmental and socioeconomic burdens while maximizing economic and social values.

The use of the term *human health*[1] in this guidance generally pertains to emissions in the remediation project life cycle that could potentially impact human health and does not generally include the traditional human health risks developed as part of the human health risk assessment. For example, the transport of activated carbon to a site results in emissions (i.e., from truck exhaust) of particulate matter that can potentially impact human health. While the impacts of these emissions are not within the boundaries of the remediation project site (or maybe even the same country), the emissions represent a potential impact to human health (e.g., respiratory health).

Awareness of the importance of environmental protection and the possible impacts associated with products or activities has increased in the remediation industry over the last several years. Remediation practitioners have responded by developing methods to better understand these impacts along their life cycle or value chain. One basic tool that can be used is life-cycle assessment (LCA), standardized by the International Organization for Standardization (ISO, 2006a, 2006b).

LCA is a compilation and evaluation of the inputs and outputs and the current or potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's or project's life cycle—from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., "cradle to grave"). In general, LCA can assist in:

- identifying opportunities to improve the environmental performance at various points in a projects life cycle;
- informing decision makers in industry, government, or nongovernmental organizations (e.g., for the purposes of strategic planning, priority setting, and process design or redesign); and
- selecting relevant indicators of environmental performance, including measurement techniques.

LCA then is a key tool for improving resource efficiency—it allows companies and other stakeholders to identify "hotspots" along the project life cycle, as well as potential

Remediation DOI: 10.1002/rem

risks and opportunities for improvements. The broad scope of LCA ensures that tangible improvements are made as it measures effects *across* the life cycle, which prevents the shifting of burdens to other types of environmental impacts or other stages of the life cycle.

Although some practitioners are conducting footprint analysis and LCA for remediation projects, a commonly accepted or standard approach for doing so is needed. Even when similar tools are used, the approaches used are inconsistent. The lack of a standard approach for conducting and documenting footprint analyses and LCAs can threaten the credibility of the conclusions derived from these efforts because different results can be obtained when inconsistent approaches are used. The uncertainty created by using different approaches can be a cause of concern for decision makers and stakeholders.

General limitations and concerns with the current footprint analysis and LCA approaches used by remediation practitioners are listed below.

- Practitioners lack appropriate training for the correct use and interpretation of results provided by tools.
- Comparison of alternatives on the basis of a similar function is not typically addressed. Also, the time horizon for remediation is often variable between alternatives, and this variable is not addressed in the definition of the function the footprint analysis or LCA is assessing.
- Practitioners begin with a preferred tool and populate the required input fields without first establishing the scope and goals of the study. As a result, the tool indirectly defines the study goal and scope, which can result in a limited understanding of the impacts for the project being evaluated.
- The goal and scope of the study are not clearly defined, leading to confusion as to what the results represent.
- The boundaries of the study are not clearly defined. In some cases, the boundaries are defined by the tool and the associated data used to estimate impacts. Often, the practitioner using the tool is unaware of the boundaries the data represent. In other cases, practitioners are using data from different sources and unknowingly mixing data sets with different boundaries or data quality.
- The sensitivity to important parameters is not evaluated to determine their effect on results. For example, the results of a study can be driven by one project element, which itself may be represented by data of low confidence.
- The results of the study are simply referenced without interpretation of their meaning, relevance, and importance for decision making.
- Documentation of the study lacks transparency, which raises questions regarding the assumptions and data inputs used.

The lack of a standard approach for conducting and documenting footprint analyses and LCAs can threaten the credibility of the conclusions derived from these efforts because different results can be obtained when inconsistent approaches are used.

These limitations and concerns can be attributed to, in part, the lack of a commonly accepted and implemented approach to conducting footprint analyses. While LCA documentation is typically more rigorous than footprint analysis, some of the limitations listed above are present in published LCAs for remediation projects (Morais & Delerue-Matos, 2010). This guidance provides an approach that avoids the limitations listed above while providing the standardization needed to perform and document studies.

Throughout the past several years, some remediation practitioners have raised the prospect of using commercial LCA tools (e.g., SimaPro® and GaBi®), comprehensive databases (e.g., Ecoinvent®), and the recognized standards for LCA (ISO, 2006a, 2006b) to conduct assessments. Although these approaches would provide the necessary standards, tools, and databases to address the limitations noted previously, many remediation practitioners consider these approaches too costly to implement.

The guidance described herein is designed to spur the use, acceptance, and consistency of the lifecycle approach for remediation. "Framework for Integrating Sustainability Into Remediation Projects" (Holland, 2011) outlines three different tiers that can be used for assessing remediation project sustainability. This guidance can be utilized in Tier 2 and Tier 3 evaluations that are quantifying emissions and impacts.

Through the application of a footprint analysis or LCA and with the help of this guidance, remediation practitioners and decision makers can reduce burden shifting and unintended consequences of remediation.

SURF recognizes that it has taken many years for the methodologies used to apply risk assessment and conduct environmental impact statements under the National Environmental Policy Act (NEPA) to become consistent and accepted. These methodologies are now considered valuable in helping to make better project decisions. Similarly, it may take several years for the integration of life-cycle thinking and the use of standardized approaches to become consistent and accepted in the remediation industry.

This guidance promotes the use of footprint analysis and LCA and, as a result, allows better-informed remediation decisions to be made. Through the application of a footprint analysis or LCA and with the help of this guidance, remediation practitioners and decision makers can reduce burden shifting and unintended consequences of remediation.

BACKGROUND AND CURRENT STATUS

Although LCA has been used for several decades in some industries to provide a better understanding of the life-cycle impacts of products on the environment and human health, LCAs have been sparingly applied in the remediation industry. Morais and Delerue-Matos (2010) identified 12 papers in LCA literature that focused on site remediation. While a formal survey of current industry practices regarding LCA has not been performed, SURF is confident that the application of LCA or any type of comprehensive quantification of the environmental footprint of a remediation project was infrequent and rare through the end of 2010.

Leading remediation practitioners are considering footprint analysis and LCA results when selecting remedial alternatives, determining the appropriate equipment and methods for implementing selected remedies, and developing optimization strategies. In some cases, these practitioners are incorporating footprint analysis and LCA results into formal documents such as feasibility studies, design reports, operating reports, and optimization studies. Those remediation practitioners who have estimated the environmental footprint of various remedial alternatives or optimized a single remedy have identified value in the effort. The results and conclusions from estimating the environmental footprint of a remediation project inform the decision-making process and may influence the selection of a remedial alternative. Additionally, when optimizing a single remedy or a design, the effort of estimating environmental impacts generally results in the identification of cost-effective optimization opportunities that reduce the environmental footprint of the remedy. Regardless of the outcome, the mere process of performing an environmental footprint analysis or LCA helps remediation practitioners:

- understand the potential environmental and human health burden of the remedy, including offsite impacts;

Remediation DOI: 10.1002/rem

- identify opportunities to reduce the burden of the remedy;
- understand the trade-offs of different decisions as they relate to transferring burdens from one impact category to another;
- understand the correlations of some decisions;
- create awareness of the benefit of using recycled or waste materials; and
- recognize that, in many instances, reducing the environmental footprint of a project results in lower overall project life-cycle costs and benefits to the community as well (e.g., less disturbance).

GUIDANCE DESIGN AND APPLICATION

The ISO standards for LCA in ISO (2006a, 2006b) are the basis for this guidance document. These standards were selected because they provide a systematic approach for the preparation of an LCA and its interpretation. Despite the availability of these standards, SURF recognizes that LCAs can be difficult to apply, particularly for users to which LCA is a relatively new concept. As a result, this guidance has been tailored specifically for use by the remediation industry in an effort to bring more standardization in how environmental impacts are quantified and documented for remediation projects. It is not intended to replace the ISO standards in cases where practitioners currently follow those standards for completing an LCA.

This guidance provides remediation practitioners the opportunity to develop a more holistic view of a remediation project by applying and integrating a footprint analysis and LCA into all phases of the remediation project life cycle:

To achieve site closure, remediation practitioners identify the decommissioning practices that reduce the impacts of system deconstruction and site restoration and optimize the site for future potential reuse.

- *Site Planning and Investigation*. During this phase, remediation practitioners identify the project stakeholders, overall local and regional issues that may apply to the project, and the data needed for use in later phases of the project life cycle.
- *Remedy Selection*. Remediation practitioners compare remedial alternatives in this phase and ultimately select a remedy. Selected metrics and opportunities for alternative improvements are considered in this phase. Refined alternatives are re-evaluated, and a remedy is selected.
- *Remedial Design and Construction*. In this phase, remediation practitioners identify opportunities to optimize the components of the selected remedy, evaluate low-impact construction practices, and explore material substitution opportunities.
- *Operation and Maintenance (O&M)*. Throughout this phase, remediation practitioners periodically evaluate the operati ng system for opportunities to reduce the footprint of the remedial action.
- *Closure*. To achieve site closure, remediation practitioners identify the decommissioning practices that reduce the impacts of system deconstruction and site restoration and optimize the site for future potential reuse.

This guidance promotes the use of footprint analysis and LCA in the above project phases and, as a result, allows better-informed remediation decisions to be made. This guidance focuses on environmental impacts and the broader human health and ecological impacts not typically addressed by regulatory requirements, human health risk assessments, or ecological risk assessments. Although the steps outlined in this guidance can also be applied to the social and economic domains of sustainability, discussion of these topics is outside of the scope of this guidance.

Explanation of Terms

For the purposes of this guidance, an *LCA* is an assessment that considers the full life cycle of the components of a remediation project, from cradle to grave. An LCA has the following attributes:

SURF believes that a footprint analysis and LCA can better inform the decision-making process in all phases of the remediation project life cycle and that their application should be considered on all remediation projects.

- utilizes an inventory of emissions for materials, energy, processing, transportation, and waste scenarios;
- allows the selection of impact categories that are the most meaningful for the goal and scope of the project;
- employs the characterization of emissions to impact categories (i.e., aggregates emissions that could impact an environmental category, such as smog formation, and uses characterization factors to convert all emissions into an equivalent constituent, such as nitrogen oxide equivalents); and
- generally requires the use of commercial tools that require specific training.

An LCA should follow the requirements defined in the ISO standards (i.e., ISO, 2006a, 2006b). Although practitioners generally use commercial LCA tools with access to comprehensive databases, it is possible to complete a LCA without commercial tools.

A *footprint analysis* is not as complete or rigorous as an LCA. A footprint analysis is characterized by the following typical attributes:

- uses predetermined metrics (e.g., using an industry-specific tool or the intellectual property tool of an industry service provider);
- accepts incomplete emission information for specific materials, energy, processing, transportation, and waste scenarios; and
- uses limited impacts and emissions (e.g., only considers climate-change potential [CCP] while evaluating other emissions that are not characterized using impact-assessment methods).

While it is recognized that an LCA is the "gold standard" for informing decision makers of potential environmental impacts, SURF also recognizes that it may be impractical to conduct LCAs on all remediation projects. Remediation decisions, albeit less informed ones, can be made based on the results of footprint analyses.

SURF believes that a footprint analysis and LCA can better inform the decision-making process in all phases of the remediation project life cycle and that their application should be considered on all remediation projects. The question of when to use a footprint analysis versus an LCA depends on many factors, including the complexity of the project, the number of inputs and outputs of the project, and stakeholder perspectives on LCAs and footprint analyses.

Some stakeholders are only interested in CCP; a footprint analysis may be appropriate for these types of projects because these tools do a good job of estimating CCP. Other projects may only have primary inputs of fuel and electricity and outputs as emissions from these inputs. Again, a footprint analysis may be appropriate for this type of project

Remediation DOI: 10.1002/rem

because footprint analysis tools do a good job of collecting important (albeit not all) emissions associated with these flows. A project that involves the use of large amounts of chemicals and other material products (e.g., landfill liners, cement, activated carbon) would be better assessed with an LCA because LCAs can do a better job of identifying how the burdens are distributed across a large number of impact categories.

Some additional key terms that are used in this guidance document are defined below:

- *Inventory* refers to the compilation of inputs and outputs of the remediation system being evaluated. It is derived from the material components of the remediation systems (e.g., steel pipe, activated carbon), the energy that is used in the system, and the waste the system releases. These individual components are further broken down into discrete raw material inputs, chemical input and emissions, energy, and waste.
- *Cut-off criteria* refer to the amount of material or energy flow or the level of environmental significance associated with the remediation system below which an input may be excluded from the footprint analysis or LCA. For example, exclusion of some consumables (such as the use and disposal of personal protective equipment) in a study may be appropriate if the practitioner is confident that it is not environmentally significant.
- SURF defines the term *metric* as "key impacts, outcomes, or burdens that are to be assessed or balanced to determine the influences and impacts of a remedial action" (Butler, 2011, p. 81).
- *Characterization factor* is derived from a characterization model and is applied to convert individual life-cycle inventory flow amounts to the common unit of the category indicator (e.g., the characterization factor for methane is 25 for CCP—that is, 1 kilogram [kg] of methane is equivalent to 25 kg of carbon dioxide equivalents).
- *Impact category* represents an environmental issue of concern to which life-cycle inventory results may be assigned (ISO, 2006a, 2006b) (e.g., methane emissions to air are assigned to CCP).
- *Impact category indicator* represents the quantifiable measure of the impact category (ISO, 2006a) (e.g., carbon dioxide equivalents).
- An *impact assessment* is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts (typically several) plus additional quantified results that are not included in the traditional impact categories evaluated in LCAs (e.g., potential for injury or fatality based on truck miles driven on the road). In the case of a footprint analysis, carbon dioxide equivalents are typically the only quantified impact category. The remaining footprint analysis results are typically emissions identified in the inventory phase (e.g., sulfur oxides, nitrogen oxide, and particulate matter).
- *Infrastructure* refers to equipment and systems used to produce and support components of projects. For example, if infrastructure was used for truck transportation, the manufacturing and maintenance of the truck and the construction and maintenance of roads would also be included by allocating a portion of the infrastructure based on the miles driven by the truck for the project.
- *Study* refers to the work of performing a footprint analysis or LCA.
- *"Cradle to grave"* means including all upstream and downstream processes of a remedy, from material/resource extraction, processing, use, and maintenance to end-of-life treatment.

- *"Cradle to gate"* considers only a specific remedy installation or phase of the remedy. For example, a cradle-to-gate LCA may be more appropriate for analyses that are comparing several treatment options that all require equivalent long-term O&M and ultimate end use. Thus, a cradle-to-gate study, meaning cradle-through-remedy-implementation, may be more relevant and save time by not including the comparable end-of-life phase.

Guidance Implementation Steps

Although the steps outlined in this guidance can also be applied to the social and economic domains of sustainability into remediation projects—and are very important factors in sustainable remediation decision making—discussion of these topics is outside of the scope of this guidance.

This guidance focuses on environmental assessment and includes the broader human health and ecological impacts not typically addressed by regulatory requirements, human health risk assessments, or ecological risk assessments. Although the steps outlined in this guidance can also be applied to the social and economic domains of sustainability into remediation projects—and are very important factors in sustainable remediation decision making—discussion of these topics is outside of the scope of this guidance.

This guidance provides an approach for conducting a footprint analysis and LCA for remediation projects. With this guidance, remediation practitioners can apply a stepwise process that instills the proper planning, execution, interpretation, and reporting of footprint analyses and LCAs. This approach provides the much-needed consistency in footprint analysis and LCA reporting and documentation and assures stakeholders that a robust and transparent process was followed.

Following the ISO standards and guidelines developed for their implementation, this guidance consists of nine steps, or considerations, for implementing footprint analyses and LCAs on remediation projects. As stated previously, remediation practitioners can use this stepwise process to evaluate the impacts of all aspects of the remediation project life cycle. The nine steps are as follows:

Define the study goals and scope.

Define the functional unit.

Establish the system boundaries. (The use of the term *system* here is broader than the remediation system and includes off-site and on-site considerations.)

Establish the project metrics.

Compile the project inventory (i.e., inputs and outputs).

Assess the impacts.

Analyze the sensitivity and uncertainty of the impact-assessment results.

Interpret the inventory analysis and impact-assessment results.

Report the study results.

These steps are presented in the sections that follow.

Step 1: Define Study Goals and Scope

Defining the goals and project scope influences the other steps of the footprint analysis and LCA because they guide the following:

- the detailed aspects of the system boundary,
- the data-gathering and impact-estimating efforts,

Remediation DOI: 10.1002/rem

- the quality control and review of the work performed, and
- the evaluation and interpretation of the final results.

Step 1 involves establishing and clearly stating the study goals, identifying the intended application(s) of the study, and identifying the targeted audience(s). Then, remediation practitioners define the study scope and boundaries as well as the level of detail required to meet the goals. During this step, it is also important to lay out the reasons for conducting the study and provide the assessment methodology.

During this step, some remediation practitioners apply the LCA concepts of primary, secondary, and tertiary impacts to studies. Primary impacts are those impacts associated with both the contaminants on-site during cleanup and the residual contaminants present after cleanup. Secondary impacts are directly associated with the cleanup activities (e.g., energy and material used for the remediation activities). Tertiary impacts are associated with the benefits or burdens provided by reuse or fate of the land (Lesage et al., 2007), which is particularly important to consider if the alternatives being compared lead to different future or end land uses. Whether or not this particular terminology is used, it is imperative to recognize all of these impacts to ensure a holistic view of the cleanup.

In addition, remediation practitioners identify the target audience(s) (e.g., site owners, regulatory agencies, the community) of the study during this step to ensure focus on the concerns of that audience. The organization of the study is set during this stage, including the interpretation of results. The appropriate modeling frameworks, evaluation approaches, and data-integration approach, and the optimal method of conveying the results (e.g., report), are also identified. While this guidance focuses only on the environmental elements of a footprint analysis and LCA, the integration of social and economic aspects of the project also need to be addressed in this step.

Primary impacts are those impacts associated with both the contaminants on-site during cleanup and the residual contaminants present after cleanup.

In summary, the goal-definition aspects of this step allow remediation practitioners to identify the purpose of the study, the questions to be answered by the study, the decisions intended to be informed by the study results, the level of detail necessary for the study, and the details of performing the study. The scope-definition aspects of this step identify the requirements for the study methodology, quality, reporting, and review in accordance with the study goals, the intended applications, and the results.

Step 2: Define Functional Unit

The system's function and the study's functional unit are central elements of a footprint analysis or LCA. The functional unit identifies the qualitative and quantitative aspects of the function(s) and generally answers the question of "what," "how much," "how well," and "for how long." As noted in the *International Reference Life Cycle Data System (ILCD) Handbook* (European Commission, 2010) and other guidelines, the system function should be described in a precise, quantitative, and qualitative manner.

The first steps in defining the functional unit are to identify the relevant properties and quantify the performance of the system; for example, the quantity of soil to be remediated to a given cleanup criterion. A functional unit describes the work being performed. The "how much" question is answered when specifying the quantity of cubic yards of soil removed in a dig-and-haul remedy. Another way to define the functional unit is in terms of a target-level approach so that vastly different cleanup techniques can be compared. Here, the equivalence is found in the ultimate reduction of a contaminant to a given level (i.e., answering the "what" question) such that the options achieve the same reduction goal (i.e., answering a "how well" question). When the time frame for a groundwater remedy is defined (e.g., 40 years), it addresses the "how long" question. For complex sites with a mixture of contaminants, the functional unit may be associated with reducing net risk below some threshold level.

Some examples of functional unit descriptions from remediation LCA literature are as follows:

For complex sites with a mixture of contaminants, the functional unit may be associated with reducing net risk below some threshold level.

Cadotte et al. (2007): The functional unit is defined as "the remediation of a 375 cubic meter (m^3) diesel-contaminated site to the. . . criterion in soil [700 milligrams per kilogram ($mgkg^{-1}$)] and to the detectable limit of C_{10}–C_{50} for potable, groundwater, and surface water. . . ." (p. 240). In this example, the "what," "how much," and "how well" elements are addressed, but the "how long" element was not specifically mentioned. However, the reference does note that different treatment times are associated with each of the alternatives evaluated and specifies those times of treatment. So while not specifically incorporated into the functional unit, the "how long" element is noted later in the evaluation.

Godin et al. (2004): The functional unit is defined as "the management of 460,000 m^3 of waste mix (including 100,000 m^3 of spent pot lining) and 200,000 m^3 of contaminated soil from the silt layer, for a period of 50 years. The 50-year-period was selected because this is the estimated time for contaminant concentrations, near the point of discharge to the aquatic environment, to reach an approximately asymptotic level under the no-intervention" (pp. 1104–1105). In this example, all four recommended components of the functional unit are addressed. The "how well" element is not a numerical standard per se but it does indicate a quantitative endpoint.

Lesage et al. (2007): The functional unit is defined as "the legal and appropriate management of legacy contamination on 1 hectare of the tracked brownfield" (p. 499). In this example, the "what" and "how much" (but only in terms of area) elements are referenced. The "how well" element is indirectly referenced by the statement referring to legal and appropriate management. The "how long" element is not addressed in the functional unit but is later addressed in the evaluation.

These examples generally conform to the goal of describing the functional unit in terms of "what," "how much," "how well," and "for how long"; however, the level of detail they provide for each element is variable, which underscores the variability of assigning functional units for remediation projects (Morais & Delerue-Matos, 2010).

Defining a functional unit for a remediation project where the study is focused on a specific process (e.g., remedial design) is relatively uncomplicated because the alternative has been selected and the study focuses on how to design and optimize the process. In general, the four elements of the functional unit described will be identical for all options evaluated. Defining the functional unit for a feasibility study where different alternatives are compared is more challenging because, generally, the conditions of the remedial alternatives vary (e.g., treatment times, contaminants left in place, resource value of the site, potential future or end use[s] of the site). When these different attributes are addressed (e.g., through system expansion, qualification, or normalization to another metric such as natural resource value), the functional unit will be more appropriate as a basis for comparison.

When defining a functional unit, often a default time for remediation of groundwater is assumed. This assumption can be practical to some practitioners because the net present

 Remediation DOI: 10.1002/rem

Exhibit 1. The functional unit challenge when comparing alternatives

Consider an example where the functional unit is as follows: "remediate contaminated soils (300 feet by 100 feet by 6 feet deep) so that no inhalation, dermal, or ingestion pathways to humans exist." Alternative 1 involves contaminated soil excavation and transportation to a landfill, and Alternative 2 involves capping the contaminated soil in place. In this case, the impacts would be represented in terms of what it takes to achieve the function for each alternative. While the impacts for each of these alternatives can be easily estimated, it is challenging to compare the impacts directly because Alternative 1 results in the unrestricted land use of the site and Alternative 2 involves land-use limitations and perpetual maintenance. So while both alternatives achieve the same remedial action objectives, the end uses of the site could be different. Therefore, the function of the alternatives is different. One approach to resolving this challenge is to express the impact results in terms of the land-use endpoints, land value, or human-use value (e.g., kg of carbon dioxide equivalents per human-use value unit or per acre-use-year). If the future land use for the site is a parking lot, the human-use value could be relatively equivalent. However, if the land is valued highly, the limitations associated with a cap could significantly impact the human-use potential and value of the site.

value cost of operation and maintenance becomes negligible as the time period is increased beyond a certain period. However, environmental impacts are not discounted over time, nor do all remediation technologies have the same footprint over the long term. Therefore, it is inappropriate for remediation practitioners to assume that all remedies being evaluated will operate for the same time frame.

An appropriate life span is defined as one of sufficient duration that accounts for long-term impacts such as maintaining a hazardous landfill site or performing long-term O&M. Remediation practitioners must integrate these time considerations into the study. Setting the time frame toward achievement of a functional unit is advantageous in that it requires practitioners to quantify the time needed to achieve site closure for each remedy and consider parameters such as contaminant destruction and mobility. If these primary impacts are adequately considered, remediation practitioners can compare different technologies that meet different target levels. Exhibit 1 provides an example of the challenges that face remediation practitioners in this step, along with potential solutions.

Step 3: Establish System Boundaries

The system boundaries define which parts of the life cycle and which processes belong to the analyzed system. A precise definition of the system boundaries is important to ensure that all processes are included in the modeled system and that all relevant potential impacts to human health and the environment are included. Establishing these boundaries allows remediation practitioners to identify and determine which materials, energy, transport, processing, and waste treatment components should be included or excluded from the footprint analysis or LCA.

The defined goal in Step 1 also informs the level of detail needed (e.g., processes within the site boundary, off-site inputs such as electricity, manufacturing and raw material extraction for materials used in the remedy, transport of workers to/from the site [if remote], sample collection, and analysis during O&M).

If remedial options are being compared, remediation practitioners must be consistent when setting system boundaries and data-quality requirements. Study boundaries can differ depending on the study objectives, the number of alternatives evaluated, and the specific alternative being studied. Such differences in boundaries and data inputs need to be discussed in this step. When establishing geographic, temporal, or technology system boundaries for remediation projects, remediation practitioners should consider the following:

If remedial options are being compared, remediation practitioners must be consistent when setting system boundaries and data-quality requirements.

- *Geographic Boundary*. This boundary defines the location of impacts to be evaluated. Boundary category examples are as follows: on-site (e.g., power used on-site for remediation systems), local (e.g., inorganic respiratory impacts due to equipment travel to, from, or on the site), regional (e.g., resource loss due to extraction of backfill material from quarry), and global (e.g., carbon dioxide emissions from equipment operation or transport of consumables).
- *Temporal Boundary*. This boundary defines the time horizon for a remediation project. Boundary category examples are as follows: site rehabilitation time frame (e.g., *in situ* thermal treatment with subsequent natural attenuation equals five years, *in situ* bioremediation equals 20 years, and natural attenuation equals 100 years), impacts incurred from initial site evaluation to completion of remediation, and impacts occurring during and after cleanup.
- *Technological Boundary*. This boundary defines the relevant systems being used. Boundary category examples are as follows: best available technology, average and/or range of technology in place, and prospective (i.e., improved or developing) technology.

Remediation practitioners could create a process map based on the system boundaries so that the system can be analyzed. Exhibit 2 shows an example of activities occurring on-site (within the capital and O&M box), including the off-site inputs used and off-site downstream activities. The impacts associated with the off-site and on-site activities are also shown. As seen in Exhibit 2, off-site impacts commonly drive LCA outcomes (e.g., fuel and off-site trucking for dig-and-haul remedies, manufacture of reagents for chemical treatment remedies).

Step 4: Establish Project Metrics

The purpose of performing a footprint analysis or LCA is to characterize the potential effects of inventory flows on aspects of the natural environment and human health. In this step, remediation practitioners evaluate impacts by first selecting a set of metrics of interest for the study.

"Metrics for Integrating Sustainability Evaluations Into Remediation Projects (Butler et al., 2011) provides a comprehensive list of remediation-specific metrics of interest that may be applicable to the various phases of the remediation project life cycle. Some of these metrics can be used to identify impact categories that should be assessed in LCAs.

Per ISO (2006a) and the *ILCD Handbook* (European Commission, 2010), the impact categories used in a study should be selected before inventory data are collected. This same thinking can be applied to metrics in footprint analyses. Selecting the metrics first allows remediation practitioners to avoid both bias and elimination of metrics because they do not help draw a conclusion desired by the practitioner. In this way, remediation

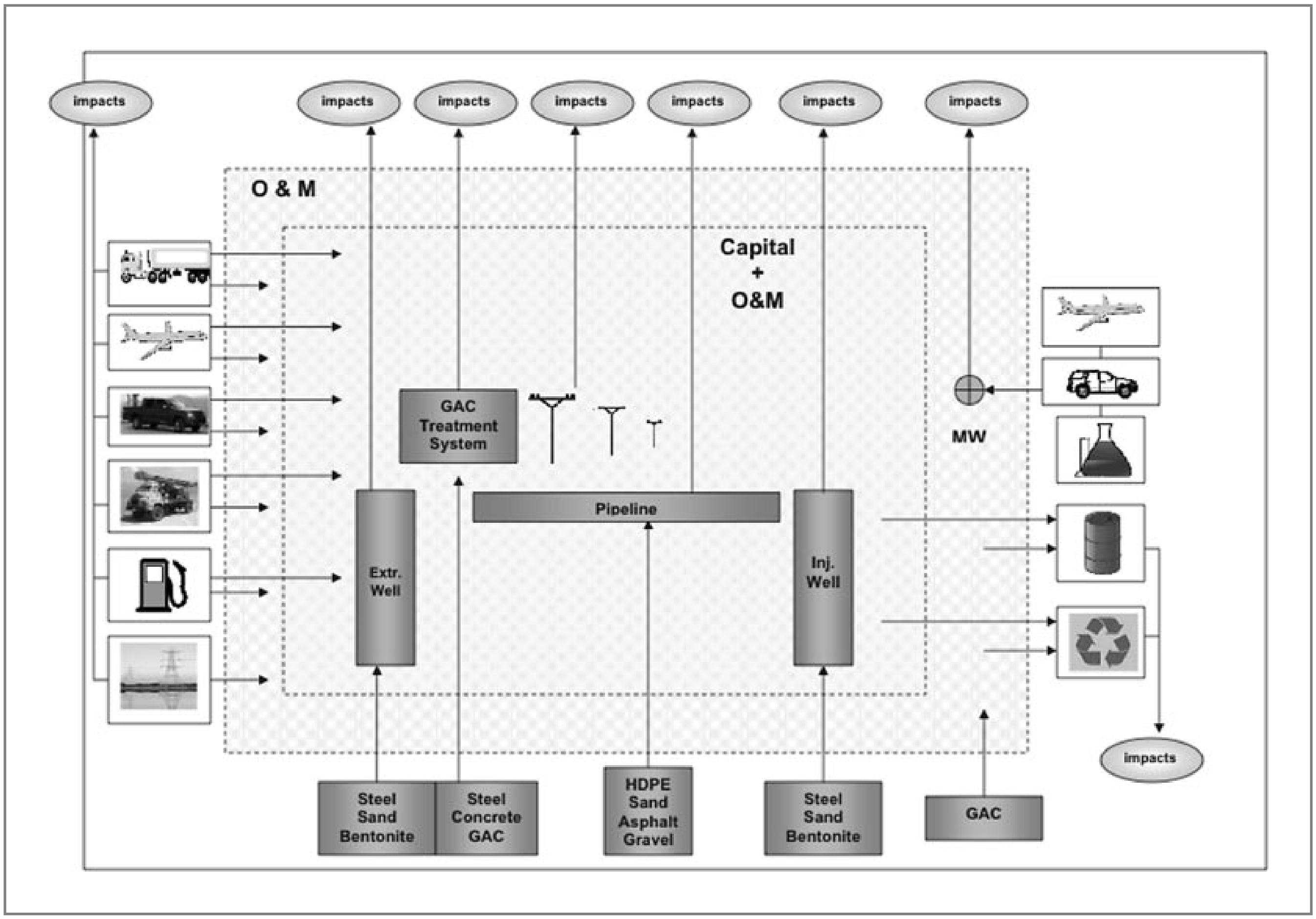

Exhibit 2. Process map for remediation project

practitioners can collect a range of data and properly scrutinize the quality of existing data with respect to the goals of the study. In general, remediation practitioners should use a comprehensive set of metrics to assure a holistic view of potential environmental impacts of the remediation project. It should be noted, however, that not all metrics have the same level of uncertainty. Although remediation practitioners can gain insight from this exercise, the uncertainty of each metric and the data quality for each metric must be understood prior to drawing conclusions.

To select the appropriate metrics for a particular remediation project, remediation practitioners must identify those metrics that are relevant to the decisions being made based on the study results and those metrics that are likely to be different among the alternatives. The iterative process of the footprint analysis or LCA can help remediation practitioners identify when certain metrics are critical or irrelevant. Remediation practitioners should document the basis for selecting each metric in the footprint analysis or LCA as well as explain the omission of a metric that appears appropriate for the study.

The explanation of why a metric is (or is not) included will help when communicating with stakeholders. Because the concept of LCA and footprint analyses is relatively new to the remediation industry, industry stakeholders are not always well versed in what the metrics and impact categories indicate (see the *ILCD Handbook* for impact-category explanations). Many in the industry appreciate such impact categories as CCP and fossil-fuel depletion because these are issues that are often discussed in the media. Other impact categories (e.g., ionizing radiation, acidification, and eutrophication) may require more explanation to help industry stakeholders better understand the important issues before making decisions.

Still, other impact categories may cause confusion due to their similarity with remediation industry–specific terms. For example, an impact category for carcinogens could be easily confused with carcinogenic risks estimated from human health risk assessments when not properly communicated. A stakeholder group that has LCA experience may need no further discussion on this impact category because they are well aware of differences between human health risk assessments and life-cycle impact assessments. Other stakeholder groups (e.g., technology professionals) may need to be briefed on the exposure model used for the impact-assessment method so they can differentiate impact results from traditional risk-assessment results. Additional communication will be needed if the results are conveyed to a stakeholder group that consists of decision makers or representatives who are not technically trained.

The first step in generating an inventory of the inputs and outputs of the remediation project life cycle is to identify all materials, energy, transport, processing, waste disposal, and waste treatment components associated with the remediation process.

Some remediation practitioners select metrics by using life-cycle tools or industry-specific tools for performing studies, such as SRT™, SiteWise™, or proprietary tools utilized by service providers. Although this approach simplifies the metric-selection phase of project planning, the number of metrics consistent with the study goals defined in Step 1 can be limited. If the goal and scope of the study requires it, remediation practitioners should track additional metrics of interest using alternative methods.

Some tools allow the inclusion of additional metrics—for example, social and economic metrics. With this in mind, remediation practitioners should explore whether additional metrics identified in Step 6 are relevant for a particular study. For example, even in the case of using commercial LCA tools that allow for a large number of impact categories to be utilized, other metrics could be considered for the analysis (e.g., the potential for worker or community safety or community economic impact of a project).

Step 5: Compile Project Inventory (Inputs and Outputs)

In this step, remediation practitioners generate a list of fundamental inputs and outputs (i.e., the inventory) by modeling one, part of one, several, or all of the following remediation phases: investigation, remedy selection, remedy design and construction, O&M, and site closure. It is important to note that the remediation phases modeled must be within the system boundaries as defined in Step 3. This step of developing the life-cycle model and generating a list of inputs and outputs and subsequent inventory requires the majority of the effort, resources, and time when performing a footprint analysis or LCA.

While the list of inputs and outputs starts with basic components such as pipe, steel, or energy, these inputs and outputs need to be converted into specific raw materials (e.g., iron ore, coal), chemicals (e.g., carbon dioxide, benzene, calcium carbonate), and emissions and energy flows (e.g., mega joules) that are part of the component's life cycle.

The first step in generating an inventory of the inputs and outputs of the remediation project life cycle is to identify all materials, energy, transport, processing, waste disposal, and waste treatment components associated with the remediation process. The inventory can be based on elements that include the project life-cycle phases and the major input and output flows such as the following:

 Remediation DOI: 10.1002/rem

- chemicals (e.g., oxidants, pH adjusters, carbon substrates, stabilizers, bioaugmentation cultures),
- finished materials (e.g., pipes, sand, concrete, bentonite, steel, high-density polyethylene tanks, tubing),
- equipment (e.g., pumps, drill rigs, generators, trenchers, skid steer loaders),
- energy (e.g., grid electricity, solar panels),
- combustion and production fuels (e.g., diesel, natural gas, gasoline, jet fuel),
- transport (e.g., equipment, materials, fuels, workers, samples, wastes),
- preferred future or end use (e.g., conversion of land to/from industrial, forest, residential), and
- contamination end-of-life (e.g., landfill, recycling, publicly owned treatment works, incineration).

It may be helpful to construct a flow diagram of the project to identify all of the inputs and outputs. An example flow diagram for the annual O&M requirements for a typical groundwater treatment plant that would be used to develop the life-cycle model and generate the inventory is presented in Exhibit 2.

Data collection is an iterative process in which additional and improved data are sought to meet the goal and scope of the study. During this step, remediation practitioners collect the following types of data:

- *Primary data* are direct emissions measurements or activity data collected from specific processes within a life cycle or from specific sources within a company's operations or supply chain.
- *Secondary data* are those data that are not collected from specific processes within a life cycle or from specific sources within a company's operations or supply chain (e.g., industry-average data, data from literature studies, and data in published databases).
- *Extrapolated data* consist of primary or secondary data related to a similar (but not representative) input, process, or activity to one in the inventory that are adapted or customized to make more representative (e.g., customizing data to a relevant region, technology, process, temporal period, and/or product).
- *Proxy data* consist of primary or secondary data related to a similar (but not representative) input, process, or activity to one in the inventory that are directly transferred or generalized to the input, process, or activity of interest without being adapted or customized to make more representative (i.e., extrapolated data without the customization).

Data collection is an iterative process in which additional and improved data are sought to meet the goal and scope of the study.

As an initial step, remediation practitioners can use literature data or simplified estimates to determine the importance of processes within the scope and ascertain the level of effort required to gather additional representative data sets. Remediation practitioners can use database or literature data instead of primary data, but this approach may limit the conclusions that can be drawn due to uncertainty. When primary data cannot be obtained, which is common when conducting footprint analyses or LCAs for remediation projects, remediation practitioners can use (listed in order of preference) secondary data, extrapolated data, or proxy data. These data can be obtained from databases, literature, or experience. In practice, these data can be a mixture of measured, calculated, or estimated data, although measured data are relatively uncommon for

Exhibit 3. ISO 14044 data-quality indicators

No.	Indicator	ISO Description
1	Time-related coverage	Age of data and minimum length of time over which data should be collected
2	Geographical coverage	Geographical area from which data for unit processes should be collected to satisfy the goal of the study
3	Technology coverage	Specific technology or technology mix
4	Precision	Measure of the variability of the data values for each data point expressed (e.g., variance)
5	Completeness	Percentage of flows measured or estimated; can be relative but should be viewed with respect to the metrics identified in the scope of the study
6	Representativeness	Qualitative assessment of the degree to which the data set reflects the true population of interest (e.g., geographical coverage, time period, and technology coverage)
7	Consistency	Qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis
8	Reproducibility	Qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study
9	Sources of the data	Documentation of the data origin
10	Uncertainty	Uncertainty of the information (e.g., data, models, and assumptions)

Source: ISO (2006).

remediation applications. Examples of data sources include the following (US Environmental Protection Agency, 2006):

- equipment information (e.g., meter readings, process specifications, and operating logs and journals);
- contractor and/or subcontractor engineering design estimates and invoices;
- vendor environmental product declarations (EPDs);
- industry data reports, databases, and consultant knowledge;
- laboratory test results;
- government and other publicly available documents, reports, databases, and clearinghouses;
- journals, papers, reference books, and patents;
- trade associations;
- related and/or previous life-cycle inventories;
- local energy provider; and
- best engineering judgment.

Remediation practitioners should evaluate the representativeness and appropriateness of the data obtained with respect to geographical, technical, and temporal aspects when considering data-quality indicators provided in Exhibit 3. When using secondary data, multiple literature sources with surprisingly different inventories may be found for a given material. Remediation practitioners should also evaluate data against the goals and scope defined in Step 1. Sensitivity analysis using different data options may be necessary if none is obviously more appropriate. Case Study No. 1 discussed in this guidance provides more detailed information about the inputs and outputs evaluated during this step.

Step 6: Assess Impacts

During this step, remediation practitioners estimate the potential environmental and human health consequences from the inventory created during Step 5. In the case of an LCA, the life-cycle inventory quantities are characterized into environmental impacts using characterization factors so that (1) a broad range of inventory data can be presented in common units or indicators and (2) large amounts of inventory information can be presented in a concise format. In the case of a footprint analysis, typically only CCP is characterized on an impact-assessment basis. Although the remainder of this section applies only to the impact assessments and is primarily focused on LCAs, it also addresses the impact assessment for CCP typically used in a footprint analysis.

Although characterization makes it easier for remediation practitioners to present the results and for the intended audience to understand the results, the basis for each characterization must be identified because some characterization factors are more commonly accepted and recognized than others. For example, the following characterization factor for CCP is widely accepted and recognized: 1 kg of methane is equivalent to 25 kg of carbon dioxide equivalents. However, a range of carcinogenic indicators and characterization factors exist depending on the specific characterization method being used. Additional information on characterization factors and interpreting characteristic impact results is provided in Chapter 4.4 of the ISO 14044:2006 standard and Chapter 6 of the *ILCD Handbook* (European Commission, 2010).

Although characterization makes it easier for remediation practitioners to present the results and for the intended audience to understand the results, the basis for each characterization must be identified because some characterization factors are more commonly accepted and recognized than others.

Impact categories are usually divided into midpoint indicators and damage or endpoint indicators. Midpoint indicators measure the potential to cause harm from a specific emission and are usually defined by a recognized mechanism. Common midpoint indicators are shown in Exhibit 4 (US EPA, 2006). In contrast, endpoint indicators extrapolate beyond the potential effects of emissions and estimate the environmental consequences on ultimate receptors or systems (e.g., damage to human health, extinction of species, and availability of resources for future generations). Endpoints also allow remediation practitioners to consolidate the numerous midpoint indicators into fewer overall damage categories.

While endpoint impact assessments may provide a context for LCA results so that results are easily understandable by stakeholders, endpoint calculations contain significant assumptions and uncertainties. Because endpoint indicators depend on models of environmental changes in addition to models of chemical fate and effects, greater uncertainty occurs with endpoint indicators than with midpoint indicators. For example, greenhouse gases are recognized to trap heat in the atmosphere (i.e., the "greenhouse effect"), which has the potential to cause climate change. CCP is a midpoint measurement of contribution to the greenhouse effect because the CCP of a substance is determined by how readily the substance contributes to the greenhouse effect in combination with how long the substance persists in the atmosphere. Desertification and species extinction are potential consequences of climate change. A measurement of the loss of ecosystem services due to desertification, species extinction, or other ecological changes caused by global warming constitutes an endpoint measurement of climate-change impacts.

Exhibit 4. Common life-cycle impact categories (midpoint indicators)

Impact Category	Scale	Relevant LCI Data (Classification)	Common Characterization Factors
Global warming	Global	Carbon dioxide (CO_2) Nitrogen dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl bromide (CH_3Br)	Global warming potential (CO_2 equivalents)
Ozone depletion	Global	CFCs HCFCs Halons CH_3Br	Ozone-depleting potential (trichlorofluoromethane [CFC-11] equivalents)
Acidification	Regional Local	Sulfur oxides (SO_x) Nitrogen oxides (NO_x) Hydrochloric acid (HCl) Hydrofluoric acid (HF) Ammonia (NH_4)	Acidification potential (hydrogen ion [H+] equivalents)
Eutrophication	Local	Phosphate (PO_4) Nitrogen oxide (NO) NO_2 Nitrates NH_4	Eutrophication potential (PO_4 equivalents)
Photochemical smog	Local	Nonmethane hydrocarbon (NMHC)	Photochemical oxidant creation potential (ethane [C_2H_6] equivalents)
Terrestrial toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}

Source: US EPA (2006).

Exhibit 5 shows a graphical representation of the structure of an impact assessment method (i.e., IMPACT 2002+ [Jolliet et al., 2003]) and illustrates the flow of life-cycle inventory results into midpoint categories (or impact categories) and the flow of midpoint indicators to damage categories.

Numerous impact-assessment methods are available for use by remediation practitioners when performing footprint analyses or LCAs for remediation projects. A summary of the more common methods, along with discussion of associated impact categories and whether the method can provide information on midpoint and endpoint impacts, is provided in Table 29 of the *ILCD Handbook* (European Commission, 2010).

Step 7: Analyze Sensitivity and Uncertainty of Impact-Assessment Results

After assessing impacts, remediation practitioners should perform sensitivity and uncertainty analyses to improve confidence in the assessment results, enhance the

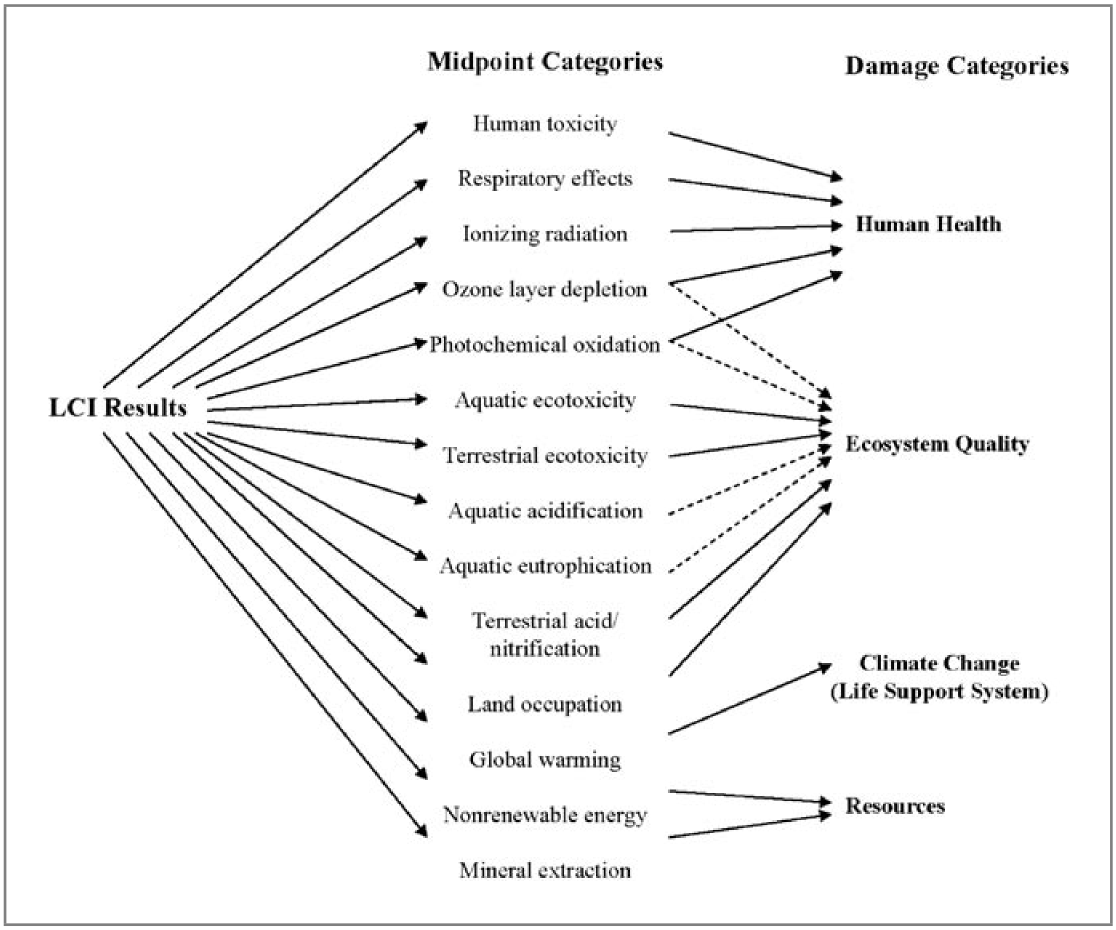

Exhibit 5. Overall scheme of the IMPACT 2002+ framework, linking life-cycle inventory results via the midpoint categories to damage categories (based on Jolliet et al., 2003)

robustness of the conclusions, and further understand the amount of uncertainty inherent within the results. In many cases, two remedial options may have different footprints when using base-case assumptions. When sensitivity and uncertainty are considered, the variability may prove these differences to be statistically insignificant.

Remediation practitioners can evaluate any input of the footprint analysis or LCA in a sensitivity analysis by identifying the key parameters that drive the results and determining how the results can change given reasonable but different inputs. A sensitivity analysis can also be used to validate cut-off criteria for input and output information, identify limitations, or assess data quality. Modeling assumptions, boundary conditions, and data sources can also be included in the analysis. Examples of appropriate sensitivity analysis for remediation projects are as follows:

- varying the amount of or type of reagent(s) used or assuming additional treatment or less treatment;
- varying the type of diesel exhaust emission technology;
- varying the electricity supply source (e.g., grid versus wind versus solar);

- expanding the remedial system boundaries (defined in Step 3) to evaluate excluded on-site or off-site processes or the importance of infrastructure;
- selecting different life-cycle data sources for key materials or reagents, or obtaining these materials from different sources (e.g., using different manufacturing processes or distances) or via different means of transport (e.g., road versus rail);
- varying allocation assumptions for co-products, usually in the manufacture of reagents or materials (e.g., consider allocation by mass, economic value, and stoichiometry);
- using virgin versus recycled materials, virgin versus regenerated granulated activated carbon (GAC), or GAC made from different raw materials (e.g., coal versus coconut husks); and
- assuming recycling or reuse of some materials or assuming different material recovery or recycling rates.

Remediation practitioners may find it useful to use powerful resources such as Monte Carlo analysis to further understand the uncertainty associated with data throughout the remediation project life cycle.

While sensitivity analysis evaluates known or controllable variables such as how electricity is obtained, uncertainty analysis addresses the unknown or imprecise inputs and assumptions (e.g., duration of the remedy). Remediation practitioners may find it useful to use powerful resources such as Monte Carlo analysis to further understand the uncertainty associated with data throughout the remediation project life cycle. As a starting point, remediation practitioners could consider performing uncertainty analysis of the following:

- *Contaminant Quantity*. Because the amount of contaminant is usually not known precisely, remediation practitioners can vary this quantity and the use rates of reagents or materials, durations of different processes, or the potential for emissions to understand the level of uncertainty associated with contaminant quantity.
- *Remedy Duration*. Because the endpoint for a remedy is not usually obvious, remediation practitioners can vary the time of remediation to understand the level of uncertainty associated with the duration of a remedy. It is important to note that not all options may have the same remedy duration or the same range of variation in the sensitivity analysis (e.g., dig-and-haul remedies generally have a shorter duration than other options). Source treatment options may have a shorter treatment time than remedies that treat contaminated groundwater. Although a default remediation time frame may be an accepted duration for an economic evaluation, it may be inappropriate for environmental impact comparison purposes.
- *Efficiency of Reagents or Capture Technologies*. Because the efficiency of reagents or capture technologies is not known and could greatly affect contaminant destruction or control, remediation practitioners can vary pumping rates or reagent application rates to understand the level of uncertainty associated with these elements.
- *Inventory Data*. Because uncertainty may exist in primary and secondary data, remediation practitioners can use life-cycle databases that provide ranges or uncertainty distributions for processes to better understand data uncertainty.

Step 8: Interpret Inventory Analysis and Impact-Assessment Results

In this step, remediation practitioners interpret the results of the inventory analysis completed in Step 5 and the impact assessment completed in Step 6. Regardless if a footprint analysis or LCA was used in the study, the interpretation of the results should "reflect the fact that . . . results are based on a relative approach, that they indicate

Remediation DOI: 10.1002/rem

potential environmental effects, and that they do not predict actual impacts on category endpoints, the exceeding of thresholds, or safety margins or risks" (ISO, 2006a, p. 16). In other words, footprint analysis and LCA are better used in comparisons than in absolute terms. With this in mind, remediation practitioners should interpret the results by identifying significant issues, evaluating the results, drawing conclusions, and making recommendations. These activities are described as follows:

Identify Significant Issues. By identifying significant issues, remediation practitioners can pinpoint the data elements that contribute most greatly to the results of both the inventory and impact assessment for each product, process, or service. Because of the substantial amount of data collected, it is typically only feasible to assess the data elements that contribute significantly to the outcome of the results. Significant issues can include the following:

- inventory parameters (e.g., processes, products, waste flows),
- impact category indicators (e.g., CCP, land use, acidification, ozone depletion), and
- key contributors to the results within the remediation project life-cycle stages such as individual unit processes or groups of processes (e.g., GAC reactivation, waste transport, oxidant production).

Evaluate Results. To ensure that products and processes are justly assessed; remediation practitioners should perform completeness, sensitivity, and consistency checks. A completeness check examines the comprehensiveness of the study, and a sensitivity check assesses the sensitivity of the significant data elements that influence the results most greatly. Sensitivity checks can include contribution analysis, sensitivity analysis, and/or uncertainty analysis. Consistency checks evaluate the uniformity of the methods used to set the remedial system boundaries, collect the data, make assumptions, and allocate the data to impact categories for each remedial option.

By identifying significant issues, remediation practitioners can pinpoint the data elements that contribute most greatly to the results of both the inventory and impact assessment for each product, process, or service.

After completing these checks, remediation practitioners should double-check the data quality of items identified as contributing to significant issues. If refinements are needed, then the process is repeated. This iterative approach allows remediation practitioners to refine the results and obtain greater confidence in the outcomes. After the results of the impact assessment and underlying inventory data have been determined to be complete, comparable, and acceptable, remediation practitioners can draw conclusions and make recommendations.

Draw Conclusions and Make Recommendations. By drawing conclusions and making recommendations, remediation practitioners can balance the potential human health and environmental trade-offs in the context of the study goals and stakeholder concerns defined in Step 1. These conclusions and recommendations can be used to help inform decision makers about the human health and environmental pros and cons, significant impacts of the remedial options, location of impacts (i.e., local, regional, or global), and the relative magnitude of each type of impact in comparison to each of the proposed options included in the study. When drawing conclusions, remediation practitioners should specifically note the limitations in the study so that decision makers can understand the confidence of the study results for decision-making purposes.

A thorough guide for the interpretation phase of a LCA is provided in Chapter 9 of the *ILCD Handbook* (European Commission, 2010).

Step 9: Report Study Results

Remediation practitioners should present study results consistent with the goal and scope of the study and the intended audience (both defined in Step 1). The report should provide a summary of the details from the aforementioned eight steps of this guidance and all pertinent information necessary for decision making to ensure transparency. Case studies published on the SURF website at www.sustainableremediation.org provide examples of report format and content. Report templates are also provided in Chapter 8 of the *ILCD Handbook* (2010), Chapter 5 of the ISO 14044:2006 standard, and on the SURF website.

In the report, remediation practitioners should provide complete and consistent documentation of the methodologies used, the systems analyzed, and the boundaries established.

In the report, remediation practitioners should provide complete and consistent documentation of the methodologies used, the systems analyzed, and the boundaries established. Practitioners should also clearly and objectively present the inventory data, impact-assessment results, assumptions, uncertainties, sensitivities, and limitations in adequate detail to allow the audience to comprehend the intricacies and trade-offs inherent in the footprint analysis or LCA.

The report should be tailored to the intended audience identified in Step 1 to maximize the conveyance of the study methods, results, and conclusions. Reporting the study results could be considered the most important step because the report serves as the communication vehicle for the study results to the decision makers. As discussed in Step 4, the knowledge of the stakeholders and decision makers reviewing the report should be carefully assessed so that the appropriate level of detail is conveyed in the report to maximize comprehension. If the knowledge of a stakeholder group is overestimated, it is likely that communicating the study results and conclusions will be challenging.

CASE STUDIES

Two case studies are presented in this guidance. In Case Study No. 1, a traditional LCA is performed using commercial LCA software and resources. In Case Study No. 2, a footprint analysis of a single issue is conducted using publicly available information and Microsoft Excel®. These two studies could be considered benchmarks in the continuum of footprint analysis and LCA tools. The first study represents the more complex assessment that utilizes commercial software and databases and requires trained individuals to perform the assessments. The second study is on the other end of the continuum and represents a study that all remediation professionals can conduct. The SRT™and SiteWise™tools can be placed between the two benchmarks on the continuum, but closer to Case Study No. 2 than Case Study No. 1. Additional case studies using SRT™and SiteWise™are provided on the SURF website (www.sustainableremediation.org).

Case Study No. 1

Case Study No. 1 highlights the capabilities of commercial life-cycle software for evaluating remedial actions. Portions of this case study are provided here to show the types of outputs available and how to implement the steps outlined in this guidance. Although all details are not shown because of space constraints, this case study demonstrates the level of detail, completeness, and transparency that should be included and reported after performing an LCA for a remediation project. A more complete version of this case study is available on the SURF website at www.sustainableremediation.org.

Step 1: Define Study Goals and Scope

This case study involves an evaluation of a groundwater treatment system utilizing both GAC and ion exchange to reduce the quantity of chlorinated alkanes, alkenes, and hexavalent chromium in groundwater. The design flow rate of the treatment system is 1,300 gallons per minute (gpm).

The proposed remedial system is modeled to meet regulatory requirements and no longer require remedial action after 30 years. The time of remediation is based on groundwater fate-and-transport modeling that showed that contaminants could be removed from the aquifer at the designed pumping rate in 29.8 years. Reduction of feed contaminant concentration to the groundwater treatment plant (GWTP) over time is ignored as a first approximation and assumed to have a step change to meet regulatory levels at the end of the time horizon (i.e., the gradual reduction of influent concentrations is not considered). The goal of this case study is to identify key areas of environmental and human health impact so that optimization opportunities can be identified. The commercial LCA software SimaPro® will be used for this study. The study was commissioned by the site owner for the purposes of exploring opportunities to reduce the environmental footprint of the proposed remedy.

The goal of this case study is to identify key areas of environmental and human health impact so that optimization opportunities can be identified.

All Feature Paras beginning with TIP should be set as boxes in the text (not as callouts).

TIP: The goal of the study should be clear and should be reflected upon when completing the remaining steps. A footprint analysis or LCA should be conducted in an iterative manner, perhaps leading to refinement of the study goal.

Step 2: Define Functional Unit

TIP: The functional unit answers the "what," "how much," "how well," and "how long" questions.

The functional unit for this study is the reduction of contaminants in groundwater to below regulatory levels in a 1,300-gpm groundwater treatment system over a 30-year period. The limits of the contamination that will be treated are defined in the Record of Decision for the site.

Step 3: Establish System Boundaries

TIP: When selecting boundary conditions, capture all impacts that could influence the results while meeting the study goal.

The boundaries for this study include all of the activities that occur at the treatment site during the O&M phase of groundwater remediation, as well as the following off-site impacts:

- impacts associated with the manufacture and transportation of materials and equipment to the site and off-site transportation of waste to a disposal facility; off-site materials, resources, and equipment tracked on a cradle-to-gate basis;
- energy provided from off-site sources, including the burdens for generating the energy; and
- on-site labor plus off-site transportation labor for delivery of materials and mobilization.

Items not included in this study are as follows:

The impact assessment method ReCiPe was selected because it provides the impact categories needed to meet the study goal.

- infrastructure associated with facilities used to manufacture materials or equipment or infrastructure used in the remedial action;
- minor and incidental materials and equipment used for the project (e.g., personal protective equipment, filter bags, laboratory containers);
- off-site labor for the manufacture of raw materials and energy (not available in existing data); and
- construction and demolition of the groundwater treatment system.

The time boundary for this study is 30 years and is based on fate-and-transport modeling completed during the feasibility study.

TIP: The boundary statement should include a description of the elements included in and excluded from the study. The reasons for excluding some elements should be included, and plans to test the validity of some exclusions should be provided. Because this study applies only to the O&M phase, other phases of the remediation project life cycle are not included

Step 4: Establish Project Metrics

SimaPro® life-cycle software was used for this study. The impact assessment method ReCiPe[2] was selected because it provides the impact categories needed to meet the study goal. ReCiPe includes CCP, fossil-fuel depletion potential, air acidification potential, human toxicity potential, and particulate matter formation potential (among others). Additional metrics of work hours and miles driven, both on- and off-site, are included to help address potential social impacts associated with accidents based on on-site labor hour statistics and off-site transportation accidents based on miles driven. Individual flows for diesel fuel use associated directly with on-site activities and transporting remediation consumables and wastes are also tracked. A complete list of metrics is presented with the case-study results in Step 6. Land transformation impact categories in ReCiPe are not included based on the high level of uncertainty in these models and the limited data available regarding flows included in these impacts. Both midpoint and endpoint impact characterizations are used for interpretation steps.

TIP: The metrics to be used should be presented and should be in line with the study goal. The result should be a broad, inclusive list of potential impact categories from which to identify specific opportunities for improvement.

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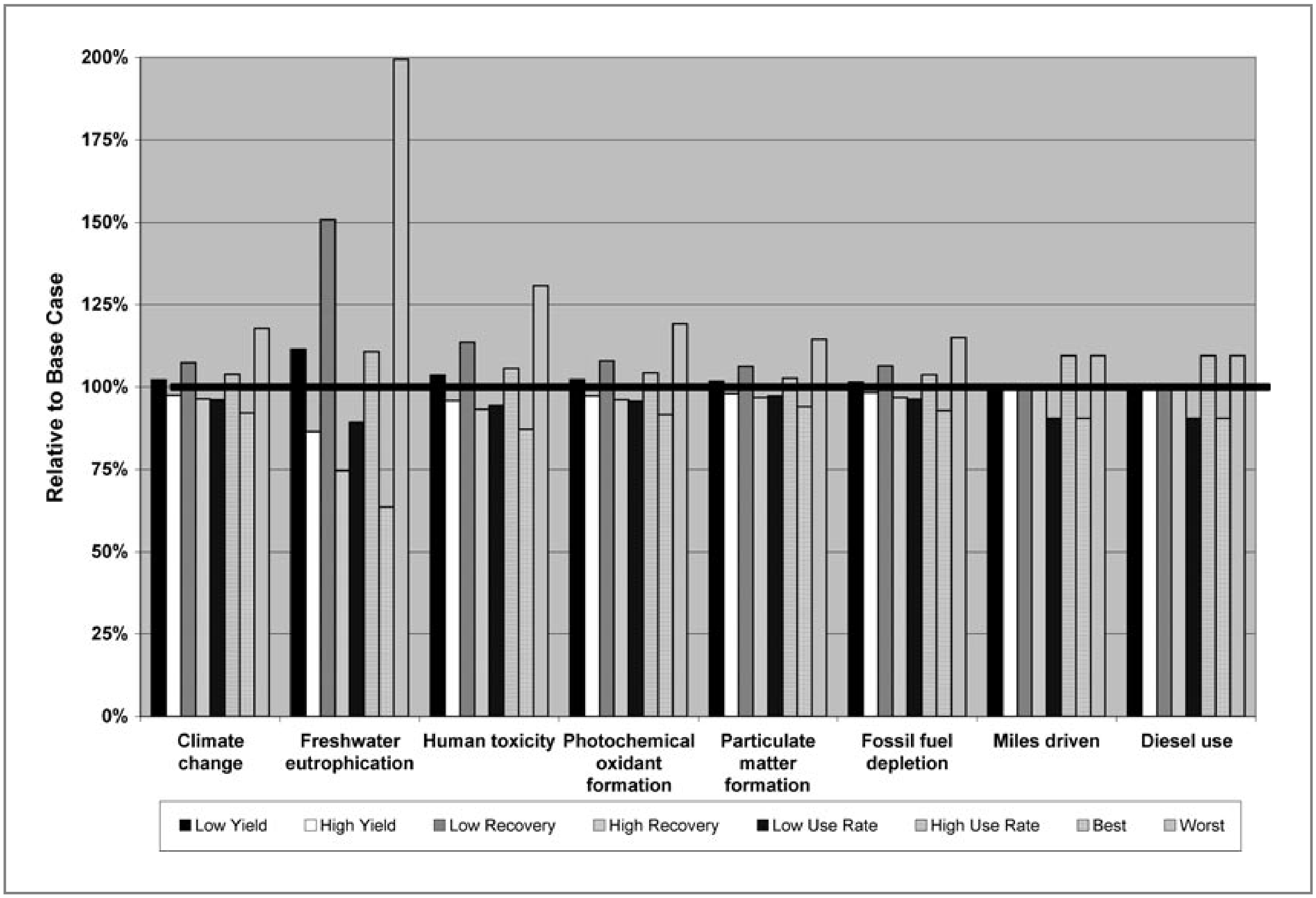

Exhibit 6. Process scheme: Ion exchange and LGAC with reclaimed water end-use

Step 5: Compile Project Inventory (Inputs and Outputs)

To develop the life-cycle inventory, the same data developed for O&M cost analysis is required because the study only covers the cleanup phase.

> **TIP:** The geographic region of the project and the data sources should be identified. Additional information on assumptions made or data adjustments should also be outlined. The objective of the inventory is to provide transparency such that the work is reproducible.

> **TIP:** For remediation projects, a cost estimate is a good place to start when identifying data sources for the study.

Inventory data were developed through detailed modeling of electricity supply, GAC manufacture, and other key materials. Exhibit 6 identifies the various electricity users, materials required, and labor requirements for the groundwater treatment facility on a yearly basis. The basis for the data selected for the major inputs to the model are provided on the next page.

- *Electricity Supply*. Secondary data were used for electricity generation from the western United States as defined by the lifecycle inventory database available within SimaPro®. (Literature data for various regions were used on a cradle-to-gate basis.)
- *GAC Manufacture*. GAC production was modeled using data available in Kirk-Othmer encyclopedia and expert information. Secondary models for charcoal briquette formation, a key raw material for GAC, were used from Ecoinvent® databases. Uncertainty in carbon yield to GAC and efficiency of reactivation were modeled through parameterization to allow for sensitivity analysis.
- *Sulfuric Acid Manufacture*. Sulfuric acid production was modeled using secondary data from Ecoinvent®. However, fuel and power consumption were changed to US life-cycle inventory sources for geographical representativeness.
- *Sodium Hydroxide Manufacture*. Sodium hydroxide production was modeled using US life-cycle inventory data that mass allocates the products from a chlor-alkali cell. A sensitivity analysis was performed where an Ecoinvent® model for sodium hydroxide production was used instead. The inventory data assumed much less production using mercury cells, resulting in minimal mercury emissions compared to the Ecoinvent® data.
- *Construction Equipment Operation*. Models were developed with estimates of diesel fuel use per hour of operation and US life-cycle inventory models for diesel fuel combustion and production. Infrastructure burdens and lubricating oil use rates for machinery were obtained from Ecoinvent® models for diesel burned in building machines, using global (worldwide) unit process models. Equipment use was modeled on a per-hour basis.
- *Raw Material Transport*. Transportation burdens for delivery of raw materials were modeled assuming a haul truck that achieves 5 miles per gallon at an average speed of 50 miles per hour while carrying up to 20 tons of material. Vehicle diesel combustion emissions from the US life-cycle inventory data were linked to this model. The amount of transport is a function of distance to be traveled and material to be moved. Infrastructure burdens for the vehicle were modeled in a similar way to the infrastructure burdens for trucks in the Ecoinvent® databases on an hourly use basis and assuming a 400,000-mile lifetime. Although not within system boundaries, infrastructure burdens were included so that the sensitivity analysis could be performed.

A partial list of the life-cycle inventory for air emissions is shown in Exhibit 7. Similar tables were developed for the raw material input and outputs (including emissions to water and land) and are available on the SURF website at www.sustainableremediation.org.

Step 6: Assess Impacts

The results of the ReCiPe impact categories for midpoint indicators are shown in Exhibit 8. The land transformation impact categories have been omitted. The results show both the total impacts and the burdens from analytical processes, the production and transportation of GAC, the production and transportation of all other raw materials (i.e., sodium hydroxide, sulfuric acid, ion exchange resin), and the production of the electrical power used on-site. The breakdown occurs within the life-cycle software through

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Exhibit 7. Life-cycle inventory: Air emissions

		Percent of Total			
Substance	**Total**	**Analytical**	**GAC Production**	**Other Chemicals and Materials**	**Electrical Power**
Carbon dioxide, fossil	55,615,843	0.1	19.2	36.5	44.3
Carbon dioxide, biogenic	742,937	0.0	2.0	23.8	74.2
Sulfur dioxide	532,561	0.0	6.5	59.7	33.9
Carbon monoxide, fossil	281,653	0.1	82.6	13.1	4.2
Nitrogen oxides	160,166	0.4	21.0	42.3	36.3
Methane	116,584	0.0	4.8	40.3	54.9
Sulfate	70,135	0.0	0.0	100.0	0.0
Methane, fossil	53,705	0.0	66.8	23.0	10.2
Particulates, unspecified	17,865	0.0	3.6	27.2	69.2
Isoprene	17,474	0.0	1.6	19.1	79.2
Nonmethane volatile organic compounds	10,409	0.2	37.9	48.3	13.6
Particulates, > 2.5 μm and < 10 μm	7,517	0.2	38.4	43.9	17.4
Particulates, < 2.5 μm	2,461	0.0	83.0	17.0	0.0
Hydrogen fluoride	824	0.0	9.7	23.2	67.1
Chlorine	543	0.0	0.0	100.0	0.0
Zinc	28.0	0.0	95.4	4.6	0.0
Lead	22.9	0.0	80.7	12.2	7.0
Nickel	12.9	0.0	46.7	36.6	16.6
Phosphorus	11.1	0.0	98.4	1.6	0.0
Vanadium	10.9	0.0	59.4	40.6	0.0
Selenium	7.7	0.0	12.3	25.1	62.6
Arsenic	6.7	0.0	65.0	11.8	23.1
Mercury	5.1	0.0	2.6	91.0	6.4
Copper	3.7	0.0	74.5	25.4	0.2
Methane, tetrachloro-, CFC-10	2.8	0.0	0.0	100.0	0.0
Cobalt	1.7	0.0	47.8	26.3	25.9
Beryllium	0.3	0.0	65.3	10.5	24.2
Methane, bromochlorodifluoro-, Halon 1211	0.1	0.0	86.4	13.6	0.0
Methane, bromotrifluoro-, Halon 1301	0.02	0.1	30.8	69.2	0.0

Notes:

All units in kilograms.

μm = micrometer.

grouping of processes. (A similar table for ReCiPe Endpoint (H) v1.03 impacts is included in the report on the SURF website.)

To better interpret these data and gauge the relative importance of a specific metric, normalization was performed. Normalization helps highlight areas of interest and areas where one should delve into with respect to confirming data quality. The equivalent

Exhibit 8. Life-cycle impact assessment: ReCiPe midpoint (H) v1.01

			Percent of Total			
Impact Category	**Unit**	**Total**	**Analytical**	**GAC Production**	**Other Chemicals and Materials**	**Electrical Power**
Climate change	kg of CO_2 eq	60,150,000	0.1	19.5	36.5	43.9
Ozone depletion	kg of CFC-11 eq	2.60	0.0	13.2	86.8	0.0
Human toxicity	kg of 1,4-DB eq	14,290,000	0.1	30.7	51.8	17.4
Photochemical oxidant formation	kg of NMVOC	264,000	0.2	21.0	40.7	38.1
Particulate matter formation	kg of PM10 eq	154,000	0.1	13.0	54.1	32.8
Terrestrial acidification	kg of SO_2 eq	634,000	0.1	9.0	57.0	33.9
Freshwater eutrophication	kg of P eq	2,390	0.0	72.8	27.2	0.0
Marine eutrophication	kg of N eq	84,900	0.3	15.9	57.0	26.8
Terrestrial ecotoxicity	kg of 1,4-DB eq	1,640	0.0	33.0	55.7	11.3
Freshwater ecotoxicity	kg of 1,4-DB eq	104,000	0.1	50.2	37.3	12.4
Marine ecotoxicity	kg of 1,4-DB eq	104,000	0.1	44.4	42.3	13.2
Water depletion	m^3	915,000	0.0	0.5	99.5	0.0
Metal depletion	kg of Fe eq	47,500	0.0	0.6	99.4	0.0
Fossil depletion	kg of oil eq	21,021,000	0.1	18.9	37.6	43.4
		Additional Metrics				
Work hours	hr	5,091,000	0.7	0.6	0.7	98.1
Work hours (on-site)	hr	5,027,000	0.7	0.0	0.0	99.3
Miles driven	mile	3,222,000	0.0	47.8	52.2	0.0
Diesel use	kg	2,081,000	0.4	47.6	52.0	0.0

Notes:

kg of CO_2 eq = kilograms of carbon dioxide equivalents.

kg of CFC-11 eq = kilograms of chloroflurocarbon-11 equivalents.

kg of 1,4-DB eq = kilograms of 1,4-dichlorobenzene equivalents.

kg of NMVOC = kilograms of non-methane volatile organic carbon.

kg of PM10 eq = kilograms of particulate mater 10 micron.

kg of SO_2 eq = kilograms of sulfur dioxide equivalents.

kg of P eq = kilograms of phosphorous equivalents.

kg of N eq = kilograms of nitrogen equivalents.

m^3= cubic meters.

kg of Fe eq = kilograms of iron equivalents.

emissions for each metric were divided by the total emissions contributing to that metric for a given country or region, and results are presented on a population equivalent basis.

Exhibit 9 shows the results of the midpoint indicator normalization for the impacts studied. The apparent large contributions from human toxicity potential and marine ecotoxicity highlighted in Exhibit 9 required these impacts to be scrutinized. Using the LCA software, the details behind the contributions to these impacts were reviewed by identifying the chemicals responsible and the processes within the supply chain that contribute these emissions. The database reports behind the life-cycle inventory data were

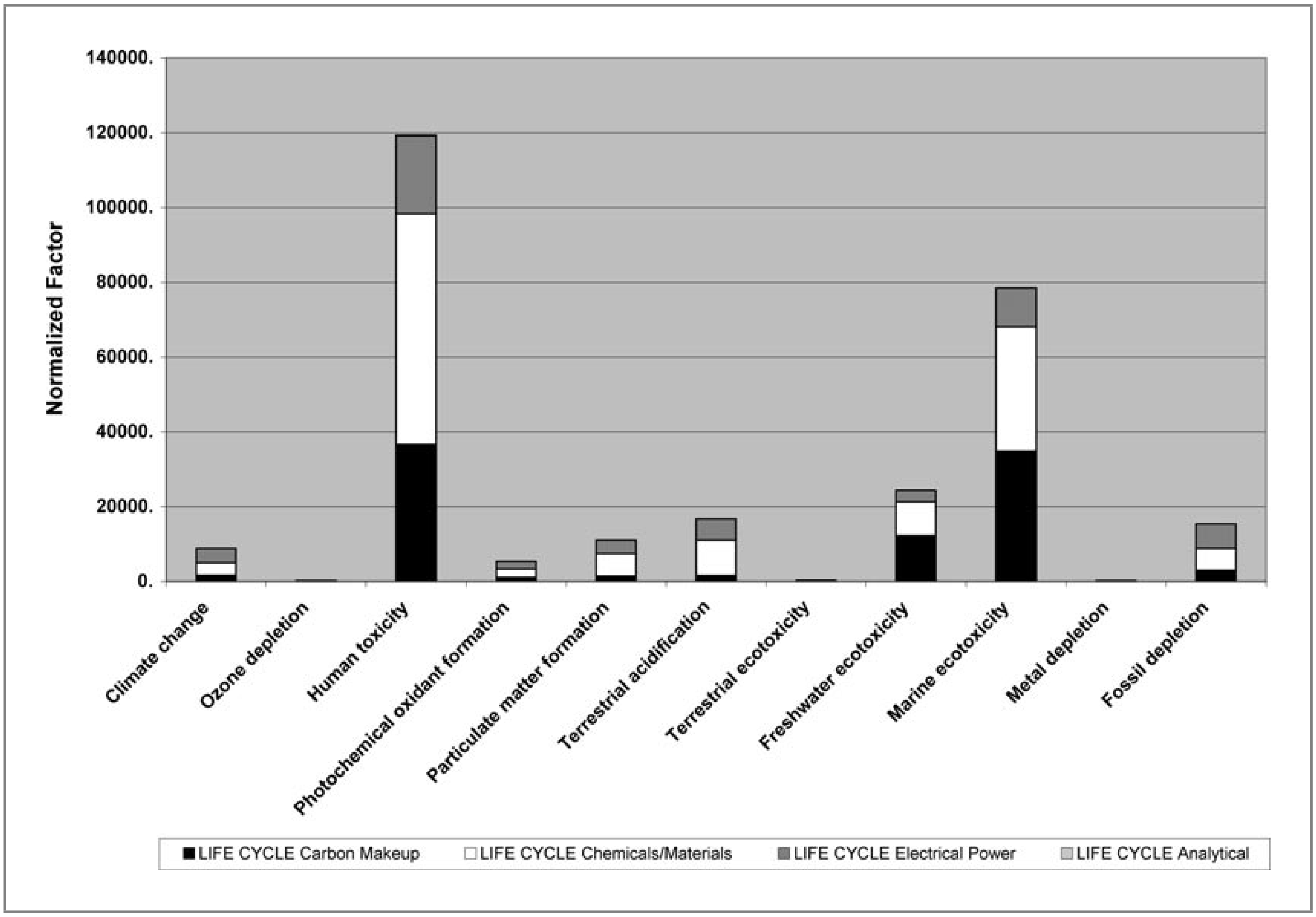

Exhibit 9. Normalized data for total impacts: ReCiPe midpoint (H) v1.01

reviewed as well. Finally, alternate impact methods were considered to further validate the results. A similar table for ReCiPe Endpoint (H) v1.03 endpoint indicator normalization results is included in the report on the SURF website.

TIP: When assessing impacts, relevant conclusions should be made and considerations about their uncertainty should be noted. Figures and information that are easy to interpret should be provided.

Step 7: Analyze Sensitivity and Uncertainty of Impact-Assessment Results

TIP: Life-cycle software makes it relatively easy to modify available data for regional differences in energy supply or for technology differences as well as for ranges for data. Key conclusions and assumptions should be tested and validated.

Characteristics with higher impacts were identified when impacts were assessed (i.e., in Step 6). Uncertainty and sensitivity analysis were performed to validate the findings documented in Step 6. Key assumptions were tested, as described on the next page.

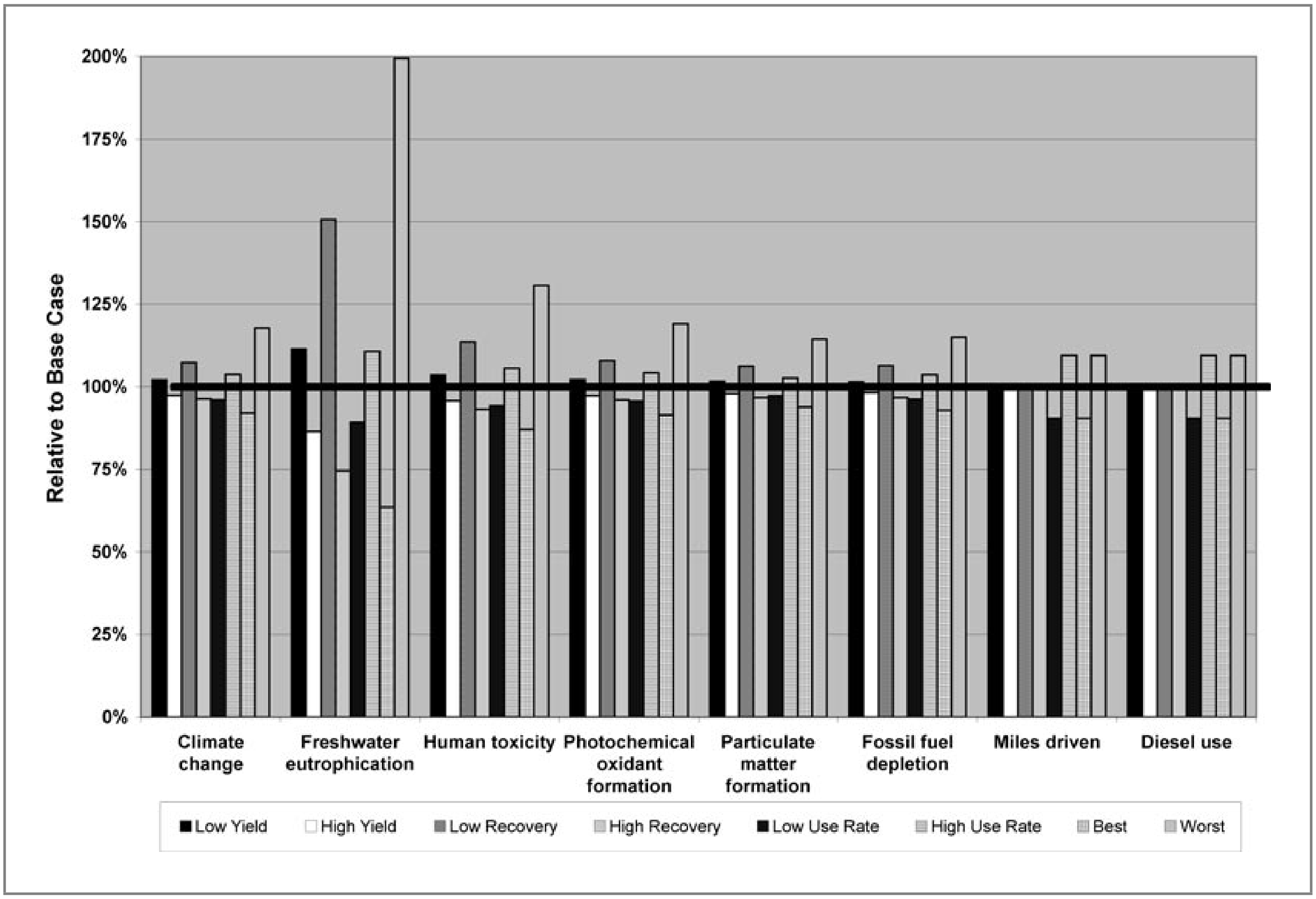

Exhibit 10. GAC sensitivity

- *GAC Use Rate, Reactivation Yield, and Production Yield*. All three of these assumptions could result in different degrees of impact from GAC production. A range of values was used for each parameter. Exhibit 10 shows that the overall results are moderately influenced by variations of any one of these parameters by about ±5 percent except for freshwater eutrophication. However, if all three variables are high or low concurrently, the variations can be about 10 percent for many categories and as much as a factor of two higher or lower for freshwater eutrophication.
- *Electricity Production and Impact-Assessment Models*. Different electricity models tend to have differences in emissions due to both fuels consumed and emissions tracked. In addition, different impact-assessment methods (i.e., comparing ReCiPe with another impact-assessment method) weight some chemicals differently. The barium emissions identified in the US life-cycle inventory electricity generation model are three orders of magnitude higher than those in US electricity models in other databases.
- *System Boundaries.* If the production and transport of raw materials are not included, more than half of the burdens of the remedy are missed in the study. Hence, the system boundaries selected are appropriate because more narrow boundaries would have overlooked many of the life-cycle burdens.

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Other sensitivity analyses results for treatment duration, infrastructure, and impact method selection (i.e., ReCiPe versus Tool for the Reduction and Assessment of Chemical and other environmental Impacts [TRACI], global versus US normalization factors] as well as uncertainty assessments are detailed in the report on the SURF website.

TIP: The results from these analyses are used to test the validity of conclusions one might draw from the base-case results. If the general trend remains the same across the range tested (i.e., parameter variation, alternate impact methods, inclusion of infrastructure), confidence in the result is improved. If making a change to a data source completely changes the importance of certain processes, then the data should be further evaluated for representativeness and data quality before drawing conclusions. If needed, the goal or scope of the study may require adjustment and the process may need to be repeated.

Step 8: Interpret Inventory Analysis and Impact-Assessment Results

TIP: To meet the study goal, burdens must be tracked back to the source upstream in the supply chain. Full life-cycle software can track these burdens and provide otherwise unavailable insights. Once an LCA model is developed, changes in the project scope can easily be evaluated to see the potential effects of changes.

Considering the assumptions, the key findings are as follows:

- Most impacts occur off-site as a result of chemical and material manufacturing and transportation.
- Overall burdens are spread somewhat evenly across GAC production, sodium hydroxide and sulfuric acid production, materials transport, and electricity supply. Improvements in any of these areas could reduce the overall burden. This finding was easily identified through Sankey diagrams generated by LCA software. (A Sankey diagram identifies material and energy flows with quantity proportional arrows in a process flow).
- GAC assumptions can influence overall burdens to a limited extent of 5 percent, with up to 10 percent for eutrophication potential.
- Sodium hydroxide supply-chain assumptions, particularly the use of mercury chlor-alkali cells and the resulting mercury emissions, drive human toxicity impacts. The use of membrane chlor-alkali cells results in lower energy use and lower potential toxicity impacts. Therefore, additional clarity from the project-specific sodium hydroxide vendor regarding manufacturing techniques should be sought. This finding was identified by tracking the emissions to the contributing process and then looking into the background reports from the secondary data source.
- Electricity supply for the facility itself attracts significant relative burdens across the impacts of interest. Methods to reduce electricity consumption or the use of renewably resourced fuel supply may potentially reduce a significant portion of the facility burden. Further analysis is required.
- Infrastructure burdens are not significant when CCP, fossil-fuel potential, or particulate-matter potential (i.e., three of the four metrics identified by normalization as of particular interest) are considered. Infrastructure has less than 12 percent additional burden for human toxicity potential. Other impact categories should be

evaluated before concluding the importance of including infrastructure. This finding was identified through sensitivity analysis.

In general, evaluating multiple impact categories, performing normalization, and conducting sensitivity and uncertainty analyses provided more insight with the intent of meeting the study goal. Areas of concern and ways to reduce overall burdens were identified. The added depth of the LCA improved the confidence of the assumptions and data in which these conclusions were drawn.

In general, evaluating multiple impact categories, performing normalization, and conducting sensitivity and uncertainty analyses provided more insight with the intent of meeting the study goal.

Step 9: Report Study Results

The narrative for the eight action steps constitutes the report for the case study. An actual LCA-based report would be longer and include more tables and figures detailing the results. The report on the SURF website (www.sustainableremediation.org) provides a more accurate depiction of a comprehensive, detailed document.

Discussion

Case Study No. 1 showed that the nine-step process for documenting a footprint analysis or LCA can be easily applied to a remediation project using commercial LCA software.

By following the nine-step documentation process outlined in this article, the data inputs, results, and conclusions that are not normally addressed in current industry reports were able to be quantified and qualified. The documentation associated with Step 8 (i.e., the interpretation of results) highlights the key findings of the study, identifies opportunities to minimize the footprint of the project, and identifies potential additional areas that could be investigated before finalizing the remediation project plans. This level of detail is important so that the conclusions of the study can be presented and communicated to stakeholders in a transparent manner.

Case Study No. 2

Case Study No. 2 is a single-issue impact evaluation of a component of a remediation project. This case study demonstrates that use of a footprint analysis could provide valuable information for decision makers even with the issue is singular and the full remediation project is not considered.

Step 1: Define Study Goals and Scope

This case study involves an evaluation that compares three different options for transporting hazardous waste from a Superfund site to a hazardous waste disposal facility. The amount of waste to be transported is 150,000 metric tons (MT). Option 1 involves transporting the waste via rail. Option 2 and Option 3 involve transporting the waste via single-unit trucks and combination trucks, respectively.

The goal of the study is to compare CCP impacts associated with each option. The study will only include midpoint impacts. The CCP for each transportation alternative will be calculated using the Intergovernmental Panel on Climate Change (IPCC) characterization factors (100-year basis) for methane and nitrous oxide to estimate the

 Remediation DOI: 10.1002/rem

carbon dioxide equivalents for each of the three options. The publicly available US Life-Cycle Inventory (USLCI) data sets for transportation by trucks and rail from the National Renewable Energy Laboratory (NREL) will be utilized. The comparison is requested by the site owner for the purposes of understanding the relative benefits of transporting waste by rail instead of truck. The single issue of CCP is being evaluated to provide additional decision-making information to support the selection of the waste transport method.

Step 2: Define Functional Unit

The functional unit for this study is the transportation of 150,000 MT of hazardous waste from the Superfund site where the waste currently resides to a hazardous waste facility. The volume of waste was derived by estimating the mass of waste that needs to be removed to comply with leachabilty-based cleanup levels for the contaminants of concern. The time frame to complete all transportation activities is estimated at three months.

Step 3: Establish System Boundaries

The boundaries for this study include only the transportation of the waste from the site to the disposal facility. Only emissions associated with combustion of fuel are considered in this study. The waste will be transported in railcars. Items not included in this study are as follows:

- infrastructure associated with truck and rail equipment used for transportation (not available in USLCI data sets),
- infrastructure associated with roads and rail (not available in USLCI data sets),
- the excavation of waste and subsequent placement in trucks (i.e., equivalent for all three options),
- the off-loading and management of waste once it arrives at the disposal facility (i.e., equivalent for all three options),
- extraction and refining of oil into a diesel product (while NREL has a dataset for extraction of oil and refining it into final products, the dataset was unclear in how impacts from extraction and refining were allocated among the numerous outputs of the process), and
- management of waste at the disposal facility since this was assumed to be identical for all three options evaluated.

The single issue of CCP is being evaluated to provide additional decision-making information to support the selection of the waste transport method.

The time boundary for this study is three months, as the transportation is expected to be completed during this time period.

Step 4: Establish Project Metrics

The only metric that will be evaluated in this study is emissions that contribute to CCP. The emissions from diesel combustion are the contributors to CCP. The specific emissions that will be estimated are carbon dioxide, dinitrogen monoxide, and methane. These

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three constituents make up the primary contributors from diesel combustion to carbon dioxide equivalents.

Step 5: Compile Project Inventory (Inputs and Outputs)

TIP: For this study, the inventory is relatively simple. The inputs include diesel from the refinery, and the outputs include the emission associated with transportation. In this case, the focus of the emissions is on the combustion products of diesel fuel.

A cost analysis was performed to estimate extending the rail line to the loading site. This option was considered cost-prohibitive given the scale and timeline of the project.

Inventory data were developed by evaluating emissions from several different transportation modes (i.e., rail, single-unit trucks, and combination trucks), all of which use diesel fuel. The inventory data were derived from the USLCI data sets for these transportation modes. The inventory only includes the diesel combustion component of the project life cycle. The haul routes and resulting distances were verified by logistic technicians for a trucking company and railroad.

As stated in Step 2, it is recognized that emissions associated with extraction and refining of oil are not included. However, it is expected that the upstream components of the fuel cycle account for less than 15 percent of the total life-cycle emissions for CCP. While this component of the life cycle is significant, it is expected that the error produced by not including the full life cycle of diesel will be consistent among the three options evaluated.

In Step 3, it was assumed that the activities associated with loading the waste on trucks or railcars were equivalent. In reality, the waste can be loaded on the trucks for transportation to the off-site disposal facility at the excavation site. For rail transport, the waste must have to be transported 10 kilometers to access the rail terminal before loading the waste onto railcars. This difference was considered insignificant and not included in the inventory. A cost analysis was performed to estimate extending the rail line to the loading site. This option was considered cost-prohibitive given the scale and timeline of the project.

The first four columns of Exhibit 11 represent the inventory for the study. The fifth column represents characterization factors (IPCC, 2007), and the sixth column represents the carbon dioxide equivalent for each inventory element.

Step 6: Assess Impacts

The inventory elements in columns 1–4 of Exhibit 11 are characterized in the sixth column and summed in the seventh column for each of the options evaluated. These values represent the impact-assessment results for CCP. The emissions in the second column of Exhibit 11 are generalized for transport by rail and truck using diesel equipment. The results from Exhibit 11 are presented graphically in Exhibit 12. Exhibit 13 shows the results in terms of metric tons and is normalized to US population equivalents.

The results show that the modes of transportation have significantly different potential CCP impact, and the rail option has the least contribution to CCP. The options using single-unit trucks and combination trucks are approximately nine and five times greater, respectively, than the rail option.

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Exhibit 11. Inventory, characterization, and impacts for Case Study No. 2

	Inventory			Characterization		Impact Assessment
	Emissions kg/tkm[1]	km[2]	Tons	IPCC Characterization Factor[3]	kg Emission (Air)—CO_2 Equivalents[4]	Total CO_2 Equivalents—kg[5]
Option 1: Rail (tkm basis)						4.29E + 06
Carbon Dioxide	1.89E-02	1,500	150,000	1	4.25E + 06	
Dinitrogen Monoxide	4.75E-07	1,500	150,000	298	3.18E + 04	
Methane	9.05E-07	1,500	150,000	25	5.09E + 03	
Option 2: Single-Unit Truck (tkm basis)						4.54E + 07
Carbon Dioxide	1.71E-01	1,750	150,000	1	4.49E + 07	
Dinitrogen Monoxide	6.19E-06	1,750	150,000	298	4.84E + 05	
Methane	4.13E-06	1,750	150,000	25	2.71E + 04	
Option 3: Combination Truck (tkm basis)						2.11E + 07
Carbon Dioxide	7.99E-02	1,750	150,000	1	2.10E + 07	
Dinitrogen Monoxide	1.99E-06	1,750	150,000	298	1.56E + 05	
Methane	1.29E-06	1,750	150,000	25	8.47E + 03	

[1] kg emissions per one ton transported over on km (from US Life-Cycle Inventory Database).

[2] km transported waste; single-unit and combination trucks have a longer route as compared to rail. As a first level approximation, only one-way transport was considered.

[3] Intergovernmental Panel on Climate Change (IPCC) 100-year time frame, 2007.

[4] represents product of three previous columns.

[5] represents summation of CO_2 equivalents for transportation mode.

The impacts associated with the truck equipment selected can have a significant impact on the results. If truck transportation is further considered, fleet-specific emission information should be used in a subsequent assessment.

Step 7: Analyze Sensitivity and Uncertainty of Impact-Assessment Results

The key sensitivity parameters are equipment selected and distance traveled. The use of two different trucks in the analysis shows the sensitivity of results to the equipment selected. Further refinement of these results can be achieved by using fleet-specific emission information. There is high certainty in the distance used to estimate impacts. However, any changes to distance will have a linear effect on the results.

Only one data source was identified for emissions associated with rail transport, so a sensitivity analysis could not be performed. If the rail option is further considered,

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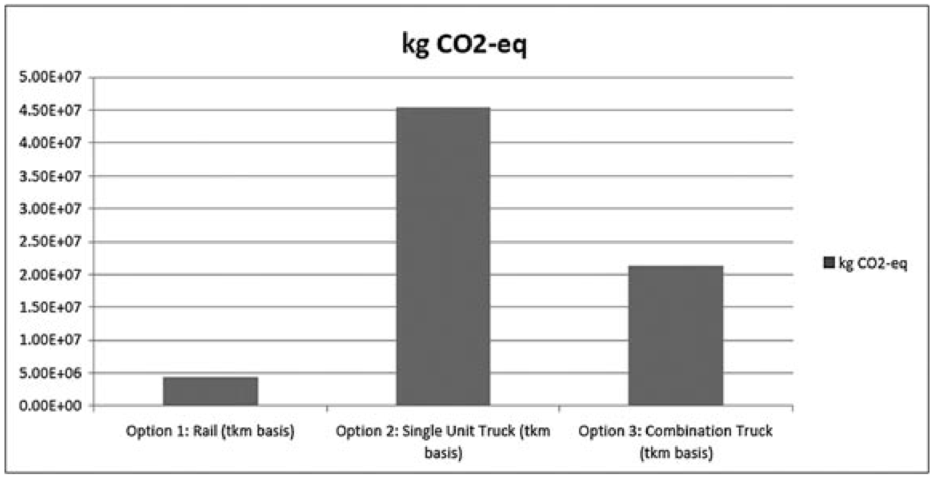

Exhibit 12. Impact-assessment results for CCP for Case Study No. 2

Exhibit 13. Impact results normalized to US person equivalents

Option	kg of CO_2 -eq	Metric Tons of CO_2-eq	US Person Equivalents[1]
Option 1: Rail (tkm basis)	4.29E + 06	4,289	195
Option 2: Single-Unit Truck (tkm basis)	4.54E + 07	45,399	2.064
Option 3: Combination Truck (tkm basis)	2.11E + 07	21,138	961

[1]22,000 kg of CO_2-eq per person per year (Lautier et al., 2010).

additional data sets should be identified to understand the variability in results as a function of equipment used.

The IPCC characterization factors are widely accepted. As a sensitivity analysis, characterization factors from the US EPA's TRACI model were evaluated. The characterization factor for dinitrogen monoxide and methane were changed to 289 (from 298) and 23 (from 25), respectively. The results changed less than 0.04 percent and would not be noticeable in the significant figures reported in Exhibits 11–13.

As stated in Step 3, the boundary of this study does not include the extraction and refining of oil to create diesel fuel. If absolute values are required for decision making, the system boundary should be expanded to include the full fuel life cycle. This could increase the potential CCP impacts by approximately 15 percent. Furthermore, infrastructure for trucks, railcars, roads, and rails could also impact results.

A sensitivity analysis considering the return trip of empty trucks was not evaluated due to the presumption the trucks were assumed to not return to the site. However, if trucks do return, the footprint of truck transportation would increase significantly.

Step 8: Interpret Inventory Analysis and Impact Assessment Results

Considering the aforementioned assumptions, the key findings are as follows:

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- The potential CCP impacts are sensitive to the mode of transportation used and distance traveled.
- The option involving rail transport is clearly preferred when considering potential CCP impacts.
- The potential impacts are sensitive to the type of truck used. Further study of this topic should utilize fleet-specific emission information.
- Only one data source for rail transport was identified. Additional data for emissions with rail transport should be evaluated to determine options for optimizing transport by rail (e.g., trains burning cleaner fuel).

The inventory only addressed the combustion of the fuel. If more precise potential CCP impact estimates are required, the system boundary should be expanded to include the upstream life-cycle components of diesel—specifically, extraction, refining, and transportation. Also, the infrastructure associated with trucks, railcars, rail lines, and roads could be significant (Facanha & Horvath, 2006) as well and may be considered.

The study did not evaluate different types of fuel (e.g., biofuel). If truck transportation is further explored, using cleaner-burning fuels could have a substantive impact on potential CCP results.

Other metrics to explore in potential future studies could include evaluating safety statistics for truck and rail travel to illuminate potential societal impacts associated with the selection of road or truck transportation. Other metrics (e.g., particulate matter, nitrous oxide, sulfur oxides) could be considered as well. Information for all of these metrics is available in the public domain.

If more precise potential CCP impact estimates are required, the system boundary should be expanded to include the upstream life-cycle components of diesel—specifically, extraction, refining, and transportation.

Step 9: Report Study Results

The narrative for the eight action steps constitutes the report for the case study.

Discussion

Case Study No. 2 showed that the nine-step process for documenting a footprint analysis can be easily applied to a remediation project using simple Microsoft Excel® calculation and graphing tools and publicly available data. The specific example utilized in this case study is typically considered a "back of the envelope"–type calculation. However, by following the nine-step process, additional insight into the evaluation was gained, and would otherwise not have been considered, such as:

- Defining the functional unit and study boundary determined what would and would not be included in the study.
- The inventory step clearly defined the inputs used to develop the inventory and the sources used to estimate the inventory. The inventory results are tied to the study boundary so a reviewer can clearly see what is and what is not addressed in the inventory. Also, a verified reference source was used for calculating inventory emissions.
- The method for characterizing the emissions is clearly documented in the footnotes of Exhibit 11. Different options for transportation were evaluated to demonstrate the sensitivity of CCP to different modes of transportation.

- The results are clearly presented in Step 8, and recommendations for additional study are provided.
- Different characterization factors were considered and reported in Step 6 to evaluate sensitivity.
- Opportunities to further optimize the footprint of different modes of transportation were provided.

Studying the footprint of the overall project could provide insight into potential opportunities to reduce the burdens associated with excavation and backfilling the waste cell.

While the study did provide an in-depth assessment of the comparative emissions of several different modes of transportation, by looking at these options, an opportunity to evaluate other opportunities to reduce the footprint of the remediation project was not identified. It is recognized that the other elements of the remediation project are considered equivalent, and their input would not change the overall decision on the mode of transport to utilize. However, studying the footprint of the overall project could provide insight into potential opportunities to reduce the burdens associated with excavation and backfilling the waste cell.

SUMMARY AND RECOMMENDATIONS

This guidance provides a background of the evolution and use of footprint analysis and LCA in the remediation industry and discusses the limitations of current practices in conducting and documenting results from these studies. A nine-step process was introduced to address these limitations and provide a consistent, transparent, and repeatable approach for conducting and documenting footprint analysis and LCA studies for remediation projects. The nine steps, along with their commensurate benefits for stakeholders and decision makers, are represented in Exhibit 14.

An important consideration in the planning and reporting of footprint analyses and LCAs is considering the knowledge of the target audience. Some elements of this guidance are technically complex and tailored communication is required to properly convey the results of the study. Likewise, several terms are used within the practice of LCA that are similar to those used in the remediation industry. The practitioner can avoid confusion by properly communicating the results so that stakeholders understand the context of these similar terms.

The two case studies presented in this guidance provide two benchmarks on opposite ends of the continuum of tools that can be used for footprint analysis and LCA. These two case studies demonstrate the flexibility of the nine-step process for a wide range of applications. The nine-step process can also be easily applied to SiteWise™and SRT™since they can be benchmarked in between the two tools used in the case studies.

The case studies provide results that would otherwise not be considered in decision making and underscore the value of following this process to better plan, conduct, and communicate results. Furthermore, by following the nine-step process and carefully documenting and evaluating the results, opportunities were identified to reduce the environmental footprint of the project.

This guidance represents the first guidance document specifically geared for conducting footprint analysis and LCA studies on remediation projects. It is flexible and can be used with the range of tools currently used in the remediation industry. By following the recommendations presented in this guidance, practitioners can apply a

Remediation DOI: 10.1002/rem

Exhibit 14. Overview of steps and benefits of nine-step process

Process Step	Benefit
1. Define study goals and scope.	Provides clear understanding of the questions being asked and a plan to answer the questions
2. Define functional unit.	Clarifies what is being assessed and evaluated and/or compared in the most representative way
3. Establish system boundaries.	Identifies what is and is not included in the assessment, including appropriate justification
4. Establish project metrics.	Identifies the metrics and methodology that will be used to evaluate and interpret results
5. Compile project inventory (inputs and outputs).	Centralizes sources of information and considerations related to defining inputs and outputs from process
6. Assess impacts.	Uses equivalency factors to characterize a range of emissions into impact categories (e.g., global warming potential)
7. Analyze sensitivity and uncertainty of impact-assessment results.	Critically evaluates data and calculation sensitivity, quality, and confidence in context of decisions being made
8. Interpret inventory analysis and impact-assessment results	Evaluates results taking into consideration results from previous steps
9. Report study results.	Documents process steps outlined above to provide transparency and objectivity of results for decision makers

stepwise process that will instill proper planning, execution, and reporting of footprint analysis and LCA studies. Reviewers of such footprint analysis and LCA studies can then be assured that a robust and consistent process was followed and that project results are presented in an objective and transparent manner. Decision makers will better understand the uncertainty and confidence of the results for decision-making purposes. For these reasons, SURF recommends that this guidance be used when performing footprint analyses and LCAs on remediation projects.

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NOTES

1. The authors considered using a term other than *human health* due to the potential for confusion with remediation industry terminology. However, because the term is well established in both the remediation industry and the practice of life-cycle assessment, we propose that practitioners clearly document the basis of the term in their footprint analysis and life-cycle assessment.
2. ReCiPe is an acronym for the three institutions that contributed to the development of the impact assessment method: RIVM (National Institute for Public Health and the Environment, Netherlands); CML (Centrum Milieukunde Leiden, Institute of Environmental Sciences, University of Leiden, the Netherlands); and Pre (PRé Consultants).

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