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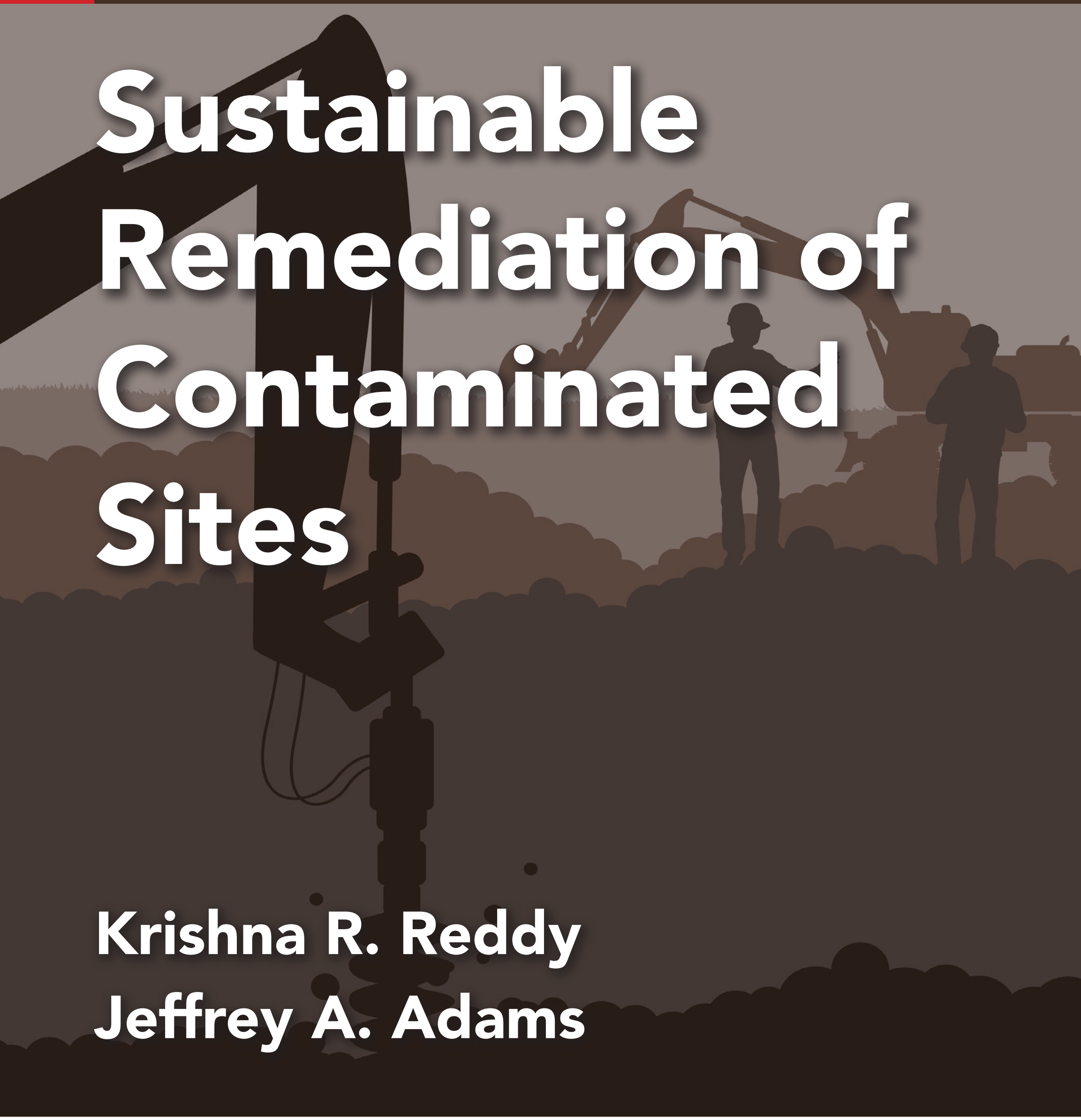

Sustainable Remediation of Contaminated Sites

Krishna R. Reddy

Jeffrey A. Adams

MOMENTUM PRESS
ENGINEERING

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ABSTRACT

Traditional site remediation approaches typically focus on the reduction of contaminant concentrations to meet cleanup goals or risk-based corrective levels, with a primary emphasis on remediation program cost and timeframe. Such an approach, however, may result in ancillary impacts to the environment that, when considered in totality with the remediation activity, result in a net negative impact to the environment. In contrast to a traditional remediation approach, this book presents a holistic approach to remediation that considers ancillary environmental impacts and aims to optimize net effects to the environment. It addresses a broad range of environmental, social, and economic impacts during all remediation phases, and achieves remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water, and soil quality through reduced emissions and other waste burdens. Inside, the authors simultaneously encourage the reuse of remediated land and enhanced long-term financial returns for investments. Though the potential benefits are enormous, many environmental professionals and project stakeholders do not utilize green and sustainable technologies because they are unaware of the methods for selection and implementation. This book describes the decision framework, presents qualitative and quantitative assessment tools, including multidisciplinary metrics, to assess sustainability, and reviews potential new technologies. It presents several case studies that include sustainable remediation solutions, and will also highlight the challenges in promoting this practice.

KEY WORDS

brownfields, environment, land contamination, life cycle assessment (LCA), remediation, remediation technologies, sustainability, sustainability development, sustainability framework, sustainability metrics, sustainability tools

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CHAPTER 1

INTRODUCTION

1.1 EMERGENCE OF ENVIRONMENTAL CONCERNS

From the 1940s through the 1960s, very little if any collective energy was focused on environmental issues. The U.S. economy and population were both growing at an unprecedented pace, and individual, private sector, and public sector goals and initiatives were directed toward providing housing, consumer, and durable goods to growing families within an expanding middle class. Additionally, the United States was engaged in an expanding Cold War and space race with the Soviet Union. Americans were aware of the environment; however, the slogan "dilution is the solution to pollution" indicated where environmental issues registered within the American psyche.

During this time, disposal practices of liquids and solids were quite rudimentary. Solids and liquids were often placed in uncontrolled dumps without any provisions for secondary containment, or in many cases, primary containment. Liquid wastes and solid wastes were also dumped into waterways without regard for chemical or thermal effects to the receiving waters. Despite some initial evolving legislation in the 1950s, air emissions from point or mobile sources were often unregulated or unchecked. As a result, the rapidly increasing pollutant loads to air, water, and soil were overwhelming the environment's ability to absorb these releases without manifested side effects. Additionally, numerous chemicals released to the environment could not be degraded through natural processes within a reasonable amount of time.

Air pollution was becoming increasingly prevalent, and notable smog outbreaks in Donora, Pennsylvania (1948), London, UK (1952), New York (1953), and Los Angeles (1954) resulted in appreciable loss of life and significant disruptions to daily activities. In response, the Air Pollution Control Act was passed in 1955. This initial legislation acknowledged that air pollution was a growing hazard to public health; however, it deferred the responsibility of combating air pollution to the individual states and did not contain enforcement provisions to sanction or hold air polluters responsible for their actions.

Water pollution was gaining notoriety with spectacular images and events. In 1969, the Cuyahoga River in Cleveland caught on fire. In fact, the river had reportedly caught fire several times prior to the 1969 event. Further, studies of the river had reported extensive visible observations of oily sheens and the absence of animal life and most other forms of aquatic life. Downstream from the Cuyahoga River, its receiving water, Lake Erie, was declared biologically dead in the 1960s. Yet, Ohio was by far not the only source of impacted water bodies—they were found in every state, and the impacts were increasing.

Buffalo, New York, exhibited significant water pollution (Niagara River, Lake Erie); however, it became even more synonymous with soil pollution. A previously abandoned canal in Niagara Falls, New York, was used as a dumping ground for thousands of tons of waste from the Hooker Chemical Company. Once the canal had been filled with waste, it was reportedly capped with clay and *closed*. Over time, a neighborhood was built over the canal (Love Canal). The resulting development and infrastructure construction pierced the clay-lined canal. Later, in the early 1950s, the local Board of Education constructed an elementary school on the canal. Over time, noxious odors were observed, and significant acute and chronic health problems were reported by the citizens. Eventually, follow-up testing and analysis determined the presence of widespread soil and groundwater contamination, and the U.S. federal government paid for the relocation of hundreds from the Love Canal area.

Several other notable environmental impacts entered the public consciousness. Among several large-scale oil platform and tanker disasters, in 1969, an offshore well accident resulted in crude oil washing ashore onto beaches along the Santa Barbara Channel in California. Additionally, nuclear fallout from above-ground nuclear weapons testing, first in the deserts of the western United States, and later in the Pacific Ocean, results in health impacts among those exposed.

These high-profile events as well as the everyday observations of *ordinary* citizens in their lives gave rise to a *grass-roots* environmental movement. Of the milestone occurrences associated with this movement, the first has been traditionally credited to the publishing of Rachel Carson's *Silent Spring* in late 1962. Ms. Carson's book observed the death of song birds, ostensibly from the uncontrolled use of pesticides for vector abatement, most notably mosquitoes. Other evidence of dichlorodiphenyltrichloroethane (DDT) use and its deleterious impact on the environment began to emerge—declining bald eagle populations in the United States were attributed to bioaccumulation of DDT, resulting in adverse effects to their eggs. Public outrage increased, and eventually DDT use was banned in the United States in 1972.

The 1969 Santa Barbara Channel oil spill also helped inspire the first observance of Earth Day in April 1970. Following the spill and federal government inaction, leaders of the political, business, and activist worlds conceived of an environmental *teach-in* to raise environmental awareness. The idea was well received by a wide range of audiences and interest groups, and millions took part in seminars, conferences, rallies, and demonstrations. Earth Day continues to this day and is celebrated in an ever-increasing number of countries by hundreds of millions of people.

Not to be discounted, the space race and the resulting ambitious scientific and engineering programs sometimes linked to environmental impacts actually inspired a growing environmental consciousness. In December 1968, while in lunar orbit, the Apollo 8 command module broadcast live images of an *earthrise* to a worldwide television audience. Given the unprecedented distance that the Apollo 8 mission traveled and the equally unprecedented images transmitted back to an enthralled audience, the images of the *blue marble* earth against the black emptiness of deep space and the starkness of the lunar surface inspired millions to realize that the earth is a fragile, discrete world worthy of protection in ways that had not been communicated or possible before the mission. Subsequent images generated during lunar missions, space station visits, and spacewalks have enforced these feelings with equally powerful images.

1.2 EMERGENCE OF ENVIRONMENTAL REGULATIONS

The major environmental events as well as the evolving public interest in environmental protection began to coalesce in the 1960s and 1970s, and the federal government began to take notice. Beginning in the 1960s and well into the 1970s, the federal government began to enact legislation designed to protect the environment. Some of these legislative acts and regulations include the following (Sharma and Reddy 2004):

- Solid Waste Disposal Act (SWDA) (1965, 1970)—the first federal legislation attempting to regulate municipal solid waste. Provisions of the law included:

  - An emphasis on the reduction of solid waste volumes to protect human health and the environment.
  - An emphasis on the improvement of waste disposal practices.
  - Provisions of funds to individual states to better manage their solid wastes.
  - Amendments in 1970 encouraged further waste reduction and waste recovery as well as the creation of a system of national disposal sites for hazardous wastes.
- National Environmental Policy Act (NEPA) (1969)—major legislation affirming the U.S. commitment to protect and maintain environmental quality. Provisions of the law included:
  - The creation of the Council of Environmental Quality, a new executive branch agency. Eventually, the Environmental Protection Agency (EPA) was created through a subsequent presidential action.
  - Requirement of the preparation of an Environmental Impact Statement (EIS) for any federal project that may have a *significant* effect on the environment. An EIS is a comprehensive document that assesses a wide range of potential impacts to the environment as well as social and economic impacts.
- Marine Protection, Research and Sanctuaries Act (MPRSA) (1972)—this law was passed to limit ocean dumping of wastes that would affect human health or the marine environment. Provisions of the law included:
  - Regulation of runoff, including those from rivers, streams, atmospheric fallout, point-source discharges, dredged materials, discharges from ships and offshore platforms, and accidental spills.
  - Prohibition of dumping of certain wastes, including high-level radioactive wastes, biological, chemical, or radiological warfare materials, and persistent inert materials that float or are suspended in the water column.
  - Permitting for all wastes to be dumped at sea.
  - Prohibition of states from enacting regulations relating to the marine environment as covered under MPRSA.
- Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (1972, 1982, and 1988)—the law was created to regulate the storage and disposal of these products. Provisions of the law included:
  - Labeling requirements for these products.
  - Registration and demonstration of usage proficiency by users of these products.

    - Registration of all pesticides with the U.S. EPA to confirm appropriate labeling and that the materials will not harm the environment.
    - Specific tolerance levels to prevent unreasonable hazards.
- Clean Air Act (CAA) (1970, 1977, and 1990)—following previous attempts at air pollution-related legislation, the CAA represented the first comprehensive law that regulated air emissions from area, stationary, and mobile sources. Provisions of the law included:
    - The establishment of National Ambient Air Quality Standards (NAAQSs) for criteria pollutants.
    - Development of standards for other hazardous air pollutants, including asbestos, volatile compounds, metals, and radionuclides where NAAQSs have not been specified.
    - Establishment of air quality regions within the United States for the purposes of regional monitoring toward the attainment or nonattainment of quality goals.
    - Later amendments established a comprehensive permitting system for various emission sources toward the regulation of several common pollutants.
- Clean Water Act (CWA) (1977, 1981, and 1987)—this law established a basic structure for the regulation of discharge of pollutants into U.S. waters. Provisions of the law included:
    - A total of 129 priority pollutants were identified as hazardous wastes.
    - Wastewater discharge treatment requirements mandating best available technologies.
    - Prohibition of discharge from point sources unless a National Pollutant Discharge Elimination System (NPDES) has been obtained.
    - Discharge of dredged material into U.S. waters is only allowed if a permit has been obtained.
    - Discharges from Publicly Owned Treatment Works (POTWs) must meet pretreatment standards.
- Safe Drinking Water Act (SDWA) (1974, 1977, and 1986)—the act was passed to protect the quality of drinking water in the United States, whether obtained from above-ground or groundwater sources. Provisions of the law included:
    - Establishment of drinking water standards, including maximum contaminant levels, primary goals, and secondary goals that provide protection of health and aesthetic standards.
    - Protection of groundwater through the regulation of hazardous waste injections.
    - Designation and protection of aquifers.

- Toxic Substances Control Act (TSCA) (1976)—TSCA was enacted to regulation and use of hazardous chemicals. Provisions of the law included:
    - Requirement of industries to report or test chemicals that may pose an environmental or human health threat.
    - Prohibition of the manufacture and import of chemicals that pose an unreasonable risk.
    - Requirement of premanufacture notifications to the U.S. EPA.
    - Prohibition of polychlorinated biphenyls (PCBs).
    - The management of asbestos is also regulated under this law.

Despite these regulatory advances, several drawbacks and limitations still existed. First, with regard to solid waste disposal, a comprehensive framework was still not in place. Preliminary efforts had been reached to classify types of wastes as well as means to properly handle and dispose of these wastes; however, the concept of *engineered landfill* still had not replaced the concept of a *dump*. Further, although the regulatory framework had been developed to address the production, storage, and use of hazardous materials, as well as regulations for controlled emissions and releases, a framework had not been developed for handling and remediating spills and other unauthorized releases of hazardous materials and petroleum products to the environment. As the 1970s wore on, incidents like Love Canal were continuing to draw the public's attention to the need for remediation of contaminated sites—and additional sweeping legislation was not far behind.

While many of the previously cited statutes and regulations were well-intended, in many cases they lacked strong enforcement or sanctioning abilities. In other cases, these regulatory frameworks induced unintended and unfavorable behaviors and actions as various entities sought to skirt regulations with newly created loopholes or exclusions. For instance, it became increasingly common for unauthorized disposal of waste to occur in ditches, vacant lots, abandoned buildings, and abandoned industrial facilities. Additionally, few regulations were in place for landfills, and other disposal methods, such as deep groundwater injection, became increasingly common (Sharma and Reddy 2004). Of course, these practices accelerated degradation of air, soil, surface water, and groundwater.

To counteract these ill-conceived and dangerous practices, the Resource Conservation and Recovery Act (RCRA) was passed in 1976. The intention of this act was to manage and regulate both hazardous and nonhazardous wastes, as well as underground storage tanks (USTs). In addition to regulations pertaining to disposal, RCRA placed an emphasis on the recovery and reuse of materials through recycling (Sharma and Reddy 2004). RCRA served as a guideline for the development of several comprehensive regulatory frameworks for the storage, generation, and disposal of wastes. Some of these regulations include the following (U.S. EPA 2011):

- Subtitle C was developed to manage hazardous wastes for its entire existence to ensure that hazardous waste is handled in a manner that protects human health and the environment (i.e., *cradle to grave*). U.S. EPA established a regulatory framework for the generation, transportation, storage, and disposal of hazardous waste, as well as technical standards for the design and operation of treatment, storage, and disposal facilities.
- Subtitle D addresses nonhazardous solid wastes, including certain hazardous wastes that are exempted from the Subtitle C regulations, including hazardous wastes from households and from conditionally exempt small quantity generators. Subtitle D also includes general household waste; nonrecycled household appliances; nonhazardous scrap and debris, such as metal scrap, wallboard, and empty containers; and sludge from industrial and municipal wastewater and water treatment plants.
- Subtitle I regulates USTs used to store hazardous substances or petroleum. Subtitle I requires owners or operators or both to notify appropriate agencies about the presence of USTs, provide a method of release detection, ensure that the tanks and piping are properly designed, constructed, and protected from corrosion, and ensure that compatibility and other performance standards are met. Requirements for reporting, recordkeeping, and financial responsibility were also established. Corrective actions pertaining to releases from USTs are also regulated under Subtitle I. Numerous exceptions are provided in Subtitle I, including small tanks or tanks used for heating oil or agricultural use, as well as septic tanks. USTs containing hazardous wastes are regulated under Subtitle C.

Additional statutes were passed in 1984 in the Hazardous and Solid Waste Amendments (HSWA). Much of the focus of these amendments was to protect groundwater, including the following (Sharma and Reddy 2004):

- Restrictions were placed on the disposal of liquids, including free liquids and specific chemicals or concentrations of chemicals.

- Requirements for the management and treatment of small amounts of hazardous wastes.
- Regulations for USTs in urban areas, including leak detection systems, inventory controls, and testing requirements. Importantly, owners of tanks were deemed liable for damages to third parties resulting from leakage.
- New standards were established for landfill facilities, including liner systems, leachate collection systems, groundwater monitoring, and leak detection.
- Specific requirements for treatment, storage, or disposal facilities (TSDF), including corrective action procedures, spill mitigation procedures, disposal bans, and five-year permit reviews. These are also applicable to inactive, formal hazardous waste disposal facilities located within RCRA facilities.
- The U.S. EPA was authorized to inspect and enforce these regulations as well as penalize violations.

While RCRA and the subsequent HSWA regulations were focused on the generation and disposal of hazardous and nonhazardous wastes, they did not address already contaminated sites. As described, many contaminated sites were emerging nationwide as a result of poor disposal and storage practices. Many of these sites posed a significant threat to human health or the environment. As a result, in 1980, the Comprehensive Environmental Response, Compensation, and Liabilities Act (CERCLA), or popularly known as *Superfund*, was passed to address cleanup of these hazardous sites. This extensive regulatory framework specifically addressed funding, liability, and prioritization of hazardous and abandoned waste sites. Some key provisions of CERCLA include the following (Sharma and Reddy 2004):

- A $1.6 billion fund was created from taxes levied on chemical and petroleum industries; this fund was set aside to finance the cleanup of hazardous waste sites. Additionally, funds were used to cover litigation costs associated with legal actions brought against potentially responsible parties (PRPs).
- In order to establish priority with respect to the relative hazards presented by contaminated sites, a hazard ranking system (HRS) was developed. Points were assigned and tallied related to factors and risks associated with contaminated sites. Once a threshold score was exceeded, a site could be placed on the National Priorities List (NPL).

- A framework was developed to outline site characterization and assessment of remedial alternatives. A remedial investigation (RI) is performed to provide a thorough assessment of site conditions. Once completed, a feasibility study (FS) is prepared to assess potential remedial alternatives against a range of criteria.

There are nine existing criteria that pertain to remediation under CERCLA. The nine criteria include two threshold criteria: (1) the overall protection of human health and the environment and (2) compliance with applicable, relevant, and appropriate requirements; five balancing criteria: (3) long-term effectiveness and permanence, (4) reduction in toxicity, mobility, and volume, (5) short-term effectiveness, (6) implementability, and (7) cost; and two modifying criteria: (8) state acceptance and (9) community acceptance.

At the time of CERCLA passage, the $1.6 billion fund was considered substantial and was believed to be adequate to fund the cleanup of all contaminated sites within five years; however, this fund soon proved to be woefully inadequate to address the contaminated sites that were identified nationwide in subsequent years. Additional funds ($8.5 billion) were appropriated in 1986 with the passage of the Superfund Amendments and Reauthorization Act (SARA). A $500 million fund was also appropriated for the remediation of leaking USTs. Additionally, community right-to-know provisions were adopted.

Most controversially, SARA specified that cleanups were required to meet applicable or relevant and appropriate requirements (ARARs). While ARARs established method for determining cleanup goals (something that was not explicitly clear in the original CERCLA statues), provisions for cleanup-related legal and financial liability were established. Disclosure requirements related to annual releases of hazardous substances were also included.

Because of explicit liability provisions directed at current landowners and related innocent landowner provisions, liability became a paramount concern for all entities associated with land transactions. As a result, standards were developed to assess the potential of contamination at properties. Three phases of environmental site assessments were developed. These include the following:

- Phase I assessments are associated with a preliminary assessment to determine the potential for environmental impact at a site. These include a site reconnaissance, historic literature review, and review of government databases to ascertain if past property uses or nearby uses may have resulted in impacts.

- Phase II assessments include actual sampling of soil, groundwater, and soil vapor to determine the extent (if any) of environmental impact at a site.
- Phase III assessments include actual environmental remediation of impacts confirmed during previous phases of study.

As with CERCLA, SARA significantly underestimated the potential costs and timing associated with environmental cleanups. When CERCLA was first enacted, approximately 36,000 contaminated sites were identified; of these, 1,200 were placed on the NPL. At the end of Fiscal Year 2010, 1,627 sites remained on the NPL, and 475 sites had been closed (OSWER 2011). However, these closures consumed a significant amount of resources; on average, $40 million was expended per site (Gamper-Rabindran, Mastromonaco, and Timmins 2011) requiring an average of 11 years to achieve closure. Further, $6 billion held in trust in 1996 had been exhausted by 2003.

Environmental statutes for many years deterred investors from acquiring properties with either confirmed or suspected environmental impact. The deterrents were three-fold. First, entering into a purchase agreement in most cases exposed a buyer or owner to significant legal liability. Second, in the absence of a defined cleanup program with regulatory oversight, it was very difficult to predict costs associated with cleanups. Third, and almost as perilous to a prospective property purchaser, in many jurisdictions, low-risk contaminated sites were not assigned priority, and therefore, were very difficult to procure agency oversight to gain closure. Because very few, if any, sources of capital will invest in properties with open cases, unknown variables with respect to agency direction or timing deterred even the most aggressive investors.

As a result, in many cases, impacted properties with significant reuse potential remained idle and sat contaminated for long periods of time. Many of these sites became known as Brownfields. A Brownfield is an abandoned, idled, or underutilized industrial or commercial site where expansion or redevelopment is complicated by actual or perceived environmental contamination (Reddy, Adams, and Richardson 1999). The real or perceived contamination can range from minor surface debris to widespread soil and groundwater contamination. Despite the extent of the real or perceived impact at a site, because of the unknowns that existed, many property owners chose not to assess potential contamination at their property because of fears associated with legal and financial exposure. Potential investors also avoided these properties for the same fears. In many cases, these sites were located in decaying urban neighborhoods and contributed to overall neighborhood blight while exacerbating other social problems. Ironically, a percentage of these sites were located in areas undergoing extensive urban renewal, yet their potential as productive land remained unfulfilled.

Much of this apprehension was the result of CERCLA law. When passed, clear statutory provisions were developed to assign responsibility and liability to all owners of a property, even those who acquired the property after the contamination occurred. Liability was also assigned even if contamination resulted from previously legal activities and practices. Because of the collective liability of all entities that appear on a chain-of-title, there has been clear motivation to avoid potentially impacted properties, as the *deep pocket* often incurs much or all of the financial liability when contamination could be uncovered.

With time, many stakeholders and regulatory agencies associated with contaminated sites realized that CERCLA-induced liability was a significant deterrent to site remediation or redevelopment. In the early 1990s, the federal government took action to provide inducements to encourage Brownfield redevelopment. In 1993, the U.S. EPA launched a Brownfields pilot program with a $200,000 grant used for a contaminated site in Cleveland, Ohio. The purpose of the grant and the program was to develop a model for Brownfield redevelopment that could be duplicated throughout the United States (Reddy, Adams, and Richardson 1999). Since then, millions of dollars in grants have been awarded to states, cities, counties, and tribes (Reddy, Adams, and Richardson 1999).

In addition to inducements to pursue the redevelopment of Brownfields, the U.S. EPA also took measures to clarify liability provisions as well as provide for indemnity for prospective purchasers. In 2002, amendments were passed to the CERCLA law requiring the U.S. EPA to promulgate regulations that established standards and practices for conducting all appropriate inquiries (U.S. Federal Register 2005). In 2005, the U.S. EPA established the All Appropriate Inquiries (AAI) requirements, which became law on November 1, 2006. The purpose of AAI was to establish liability protection under CERCLA for innocent landowners, contiguous property owners, or bona fide prospective purchasers. To establish this protection, prospective property owners must do the following (U.S. EPA 2009):

- Conduct AAI in compliance with 40 CFR Part 312, prior to acquiring the property;
- Comply with all continuing obligations after acquiring the property (CERCLA §§101(40)(C–G) and §§107(q)(A) (iii–viii)); and
- Not be affiliated with any liable party through any familial relationship or any contractual, corporate, or financial relationship (other

than a relationship created by the instrument by which the title to the property is conveyed or financed).

The AAI reporting requirements and timing are formalized in two American Society for Testing and Materials (ASTM) standards; ASTM E1527-05 "Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process" and ASTM E2247-08 "Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process for Forestland and Rural Property." These documents provide specific guidelines as to who may make the inquiries and studies, the specific activities that must be performed, and the *shelf life* of the resulting inquiry.

AAI has been a very important milestone in encouraging land acquisition and development. By establishing a framework, prospective land purchasers have a discrete set of actions they must perform to avoid open-ended liability and costs. In this manner, they can help eliminate the unknowns associated with a potential redevelopment project, which facilitates a return to productive use for many impacted properties.

Although financial and legal protections have been useful for larger projects or those that, in many cases, may have more acute environmental impacts, many more sites are impacted with low-level contamination that, while not posing a significant risk to human health or the environment, still prevent site redevelopment. In these cases, the financial implications of cleanup may be understood; however, timing issues become prohibitive factors. In many jurisdictions, regulatory agencies have opened cases for numerous low-risk properties. Often, these cases need to be closed with *no further action* (NFA) or similar status before redevelopment can proceed. Unfortunately, state agencies with increasingly limited resources did not have the time to devote to low-risk cases. As a result, even when motivated landowners or prospective purchasers had the best of intentions with respect to remediation, cases could not attract regulatory oversight and could not be remediated with the end goal of case closure. Further, in many cases where oversight could be made available, regulators and landowners often engaged in contentious relationships with respect to cleanup timelines, costs, and goals. In these cases, the lack of a positive relationship added unnecessary delays, expenditures, and problems for sites that may have been considered low-risk or straightforward with respect to remediation.

Having identified this trend, many states began to establish voluntary site cleanup or remediation programs. The goal was to create a framework in which regulatory agencies and property owners and purchasers could collaborate on a remediation program. Both parties were often motivated to achieve cleanup and closure, and a framework was needed to create action and efficiency based on this shared motivation. Although the states' programs are typically administered on an individual basis, they feature common objectives and characteristics. Commonly, the owner and purchaser and the regulatory agency enter into a formal agreement. Often the agency is reimbursed for their oversight activities. The agency and the owner and purchaser work together to establish a timeline and cleanup goals and to identify reasonable remedial system alternatives. Once the remediation has occurred, the regulatory agency issues a case closure through NFA status or similar finding.

In California, a model Brownfields program was established in late 1993. The Voluntary Cleanup Program (VCP) induces volunteer cleanup actions (the volunteer parties may or may not be responsible parties, or RPs) at eligible sites under the oversight of the California Department of Toxic Substances Control (DTSC). Prior to initiation of the VCP, DTSC focused their resources on the cleanup of state-equivalent superfund sites, impacted properties that presented a grave threat to public health or the environment (California EPA: DTSC 2008). A framework was not available for the formal closure of lower-risk or low-priority contaminated sites. As a result, these sites remained open, implicitly preventing the cleanup and restoration of these impacted properties to productive use. Project proponents enter into Voluntary Cleanup Agreements, which include reimbursement to DTSC for their oversight costs. Proponents develop a detailed scope of work, project schedule, and services to be provided by DTSC. Importantly, project proponents do not admit legal liability for site remediation upon entering into a VCP agreement. Further, a 30-day *grace period* exists where either party (the Proponent or DTSC) may terminate the project with written notice (California EPA: DTSC 1995).

Sites must be remediated to the same cleanup standards as those under DTSC jurisdiction but not within the VCP; however, the program allows for flexibility with respect to project timing and phasing (California EPA: DTSC 1995). The use of initial studies, site-specific risk assessments, and consideration of end land-use restrictions and controls are encouraged in the program to expedite the remedial process and to facilitate a remediation that is appropriate, given the envisioned future land use scenario.

Following remediation activities and the achievement of remedial action goals, DTSC may issue an NFA letter or certification of completion, depending on the project circumstances. In either case, the issuance of this finding confirms that DTSC has determined that the site does not pose a significant risk to public health or the environment. While neither constitutes a release or covenant not to sue, both significantly minimize future liability concerns. Additionally, because response actions conducted under the VCP are consistent with the National Contingency Plan, project proponents may seek cost recovery from other RPs under CERCLA (California EPA: DTSC 1995).

The California plan is similar to programs that exist in other states. Specifically, through the collaborative process, the project stakeholders can collectively assess and identify appropriate, efficient remedial alternatives. Many states require a cost-benefit analysis to study how proposed alternatives compare with respect to overall associated costs and remediation times. These programs have proven to be useful to all project stakeholders in facilitating site cleanups and restoring land to productive uses.

The move to voluntary site cleanups helped lead to the adoption of innovative site characterization and remedial technologies. The motivation was simple—with a focus on expedited, self-funded cleanups, a premium has been placed on reduced timelines and costs.

1.3 CONTAMINATED SITES: SOURCES AND TYPES OF CONTAMINATION

1.3.1 EXTENT OF THE PROBLEM

U.S. EPA estimated that there are thousands of sites that have been contaminated in the United States, and over 294,000 of these sites require urgent remedial action (Figure 1.1). The contaminated sites are often categorized by the U.S. EPA as: (1) NPL (superfund) sites, (2) RCRA corrective action sites, (3) USTs sites, (4) Department of Energy (DOE) sites, (5) Department of Defense (DOD) sites, (6) Various Civilian Federal Agencies sites, and (7) State and Private Parties (including brownfields) sites. Contamination of groundwater and soils has been a major concern at these sites. The contaminants encountered include organic compounds, heavy metals, and radionuclides. DOE sites contain mixed wastes, including radioactive wastes, while DOD sites contain explosives and unexploded ordnance. The cost to cleanup these sites is estimated to exceed $209 billion (U.S. dollars) (U.S. EPA 2012).

1.3.2 SOURCES OF CONTAMINATION

A variety of sources can cause the subsurface contamination, as depicted in Figure 1.2, and these sources of contamination may be divided into the following three groups: (1) sources that originate on the ground

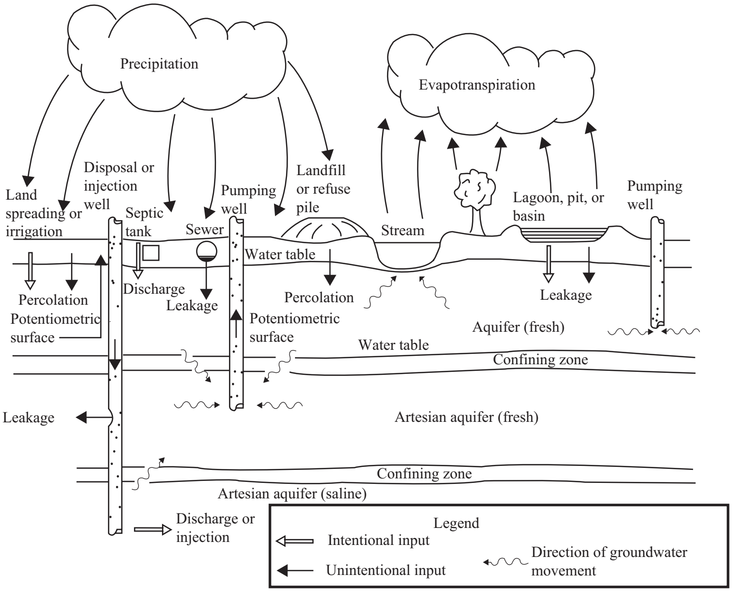

Figure 1.1. Sources of subsurface contamination.

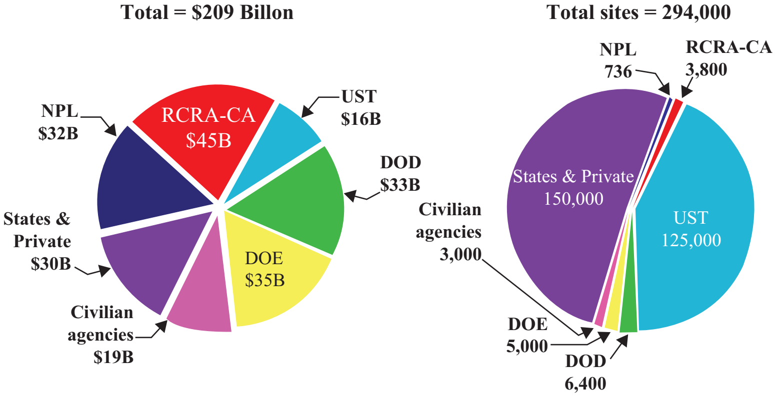

Figure 1.2. Estimated number of contaminated sites in the United States (Cleanup horizon: 2004–2033).

Source: U.S. EPA (2012).

surface, (2) sources that originate above the water table (vadose zone), and (3) sources that originate below the water table (saturated zone).

Various water-soluble products are stored or spread on the ground surface that may cause subsurface contamination. These incidents include

(1) infiltration of contaminated surface waters, (2) land disposal of solid and liquid wastes, (3) accidental spills, (4) fertilizers and pesticides, (5) disposal of sewage and water treatment plant sludge, (6) salt storage and spreading on roads, (7) animal feedlots, and (8) particulate matter from airborne sources.

A variety of substances are deposited or stored in the subsurface soils above the water table (vadose zone) that may lead to subsurface contamination. Typical events include (1) waste disposal in excavations (such as unregulated dumps), (2) landfills, (3) leachate (generated from waste decomposition and infiltration of precipitation and surface runoff), (4) surface impoundments, (5) leakage from USTs, (6) leakage from underground pipelines, and (7) septic tanks.

Numerous situations exist where hazardous materials are stored or disposed of below the water table (saturated zone) that can lead to serious groundwater contamination problems. These situations include (1) waste disposal in wet excavations (excavations, such as abandoned mines, often serve as dumps for both solid and liquid wastes), (2) mining operations (leaching of the spoil material, milling wastes, etc., below the water table), (3) deep well injection, (4) agricultural drainage wells and tiles (field tiles and drainage wells are used to drain water into deeper, more permeable soils), and (5) abandoned or improperly constructed wells.

1.3.3 TYPES OF CONTAMINANTS

Table 1.1 summarizes the most common contaminants found at the contaminated sites. This table also shows the chemical characteristics and toxicity of the contaminants as well as the major sources and pathways leading to subsurface contamination. Because of the distinctly different properties as well as the complex distribution and behavior of the contaminants in the subsurface, the remediation of contaminated sites has been a daunting task to many environmental professionals. For example, when heavy metals are present in soils, they may be distributed in one or more of the following forms: (1) dissolved in soil solution (pore water), (2) occupying exchange sites on inorganic soil constituents, (3) specifically adsorbed on inorganic soil constituents, (4) associated with insoluble soil organic matter, (5) precipitated as pure or mixed solids, and (6) present in the structure of the minerals. The amount of metals present in these different phases are controlled by the interdependent geochemical processes such as (1) adsorption and desorption, (2) redox reactions, (3) complex formations, (4) precipitation and dissolution of solids, and (5) acid-base

Table 1.1. Typical subsurface contaminants

Contaminant group	Most common contaminants in the group	Major chemical characteristics of contaminants	Toxic effects	Major sources of subsurface contamination	Causes or pathways of subsurface contamination
Heavy metals	Chromium (Cr), cadmium (Cd), nickel (Ni), lead (Pb)	Malleable, ductile, good conductors. Cationic forms precipitate under high pH conditions	Cr, Cd, and Ni can be carcinogenic with long-term exposure. Pb, Cr, Cd, and Ni are toxic with short-term exposure to large doses	Metal reclamation facilities, electroplating facilities, and other metallurgical applications, car exhaust	Atmospheric deposition, urban runoff, municipal and industrial discharge, landfill leachate
Arsenic	Arsenic, plus various inorganic forms and some organic forms	Solid at standard conditions, gray metallic color, pure as it is insoluble in water, melts at 817°C and 28 atm, sublimes at 613°C, density of 5.727 g/cm^3, 74.92 atomic mass, 5.73 sp gravity, and a vapor pressure of 1 mm Hg at 373°C	Carcinogen, high dosages will cause death	Earth's crust, some seafood, volcanoes, geological process, industrial waste, and arsenical pesticides	Weathering of soil or rocks, minerals in the soil, mining operations, coal power plants, waste water, and so on

(*Continued*)

Table 1.1. Typical subsurface contaminants (*Continued*)

Contaminant group	Most common contaminants in the group	Major chemical characteristics of contaminants	Toxic effects	Major sources of subsurface contamination	Causes or pathways of subsurface contamination
Radionuclides	Uranium (U) Radium (Ra) Radon (Rn)	U: radioactive metal Ra: radioactive metal Rn: radioactive gas	U: lung disease Ra: leukopenia, tumors in the brain and lungs Rn: pneumonia, cancer	U: nuclear weapons, power plants, accidental spills Ra: mineral deposits, rocks, soils Rn: mineral deposits, rocks, soils	U: dismantled nuclear weapons Ra: groundwater contamination, gas escapes from water and fills the air Rn: groundwater contamination, gas escapes from water and fills the air
Chlorinated solvents	Perchloroethylene (PCE), trichloro ethylene (TCE), trichloroethane (TCA), methylene chloride (MC)	Volatile, nonflammable, have low viscosity and high surface tension	Causes dermatitis, anesthetic, and poisonous	Dry cleaners, pharmaceuticals, chemical plants, electronics, and so on	Improper handling and disposal, spills, leaks from storage tanks

Polycyclic aromatic hydrocarbons (PAH)	Anthracene, benzo(a)pyrene, naphthalene	Made of carbon and hydrogen, formed through incomplete combustion, colorless, pale yellow or white solid	Carcinogen	Coal, aerosols, soot, air, creosote	Direct input, coal tar plants, manufactured gas plants, spills, garbage dumps, car exhausts
PCBs	Aroclor 1016, Aroclor 1221, Aroclor 1232, Aroclor 1242, Aroclor 1248, Aroclor 1254, Aroclor 1260, Aroclor 1262, Aroclor 1268	Water solubility (mg/L) 1.50E+01 to 2.70E–03	Cancer and noncancer effects including immune, reproductive, nervous, and endocrine systems	PCB fluid containing electrical equipment and appliances	Manufacture, use disposal and accidental spills. Can travel long distances in the air. Once in surface waters, they are taken up by aquatic animals and thus enter the food chain

(*Continued*)

Table 1.1. Typical subsurface contaminants (*Continued*)

Contaminant group	Most common contaminants in the group	Major chemical characteristics of contaminants	Toxic effects	Major sources of subsurface contamination	Causes or pathways of subsurface contamination
Pesticides	Organochlorines: DDT, dieldrin, chlordane, aldrin Organophosphates: parathion, malathion, diazinon Carbamates: aldicarb, carbofuran	Organochlorines: Low VP, low solubility, high toxicity, high persistence Organophosphates: less stable and more readily broken down than organochlorines	Chronic: cancer, liver toxicity Acute: central nervous system (CNS), respiration	Agriculture	Adsorption to soil then soil leaching, runoff to surface waters, contaminated soil comes in contact with GW table, resides in crops or livestock
Explosives	Trinitrotoluene (TNT) Cyclotrimethylene-Trinitramine (RDX)	TNT density: 1.65 g/ml; melting point: 82°C; boiling point: 240°C; water solubility: 130 g/L at 20°C; vapor pressure: 0.0002 mm Hg at 20°C	Inhalation or ingestion: gastrointestinal disturbance, toxic hepatitis, anemia, cyanosis, fatigue, lassitude, headache, delirium, convulsions, coma	Military training manufacturing and testing	Impact craters, improper design of settling lagoons containing manufacturing process waters

reactions. On the other hand, organic compounds may exist in four phases in soils: (1) dissolved phase, (2) adsorbed phase, (3) gaseous phase, and (4) free or pure phase. The organic compounds may change from one phase to another phase depending on the following processes: (1) volatilization, (2) dissolution, (3) adsorption, and (4) biodegradation. An in-depth understanding of the various geochemical processes that control the phase distribution of the contaminants in soils is critical for the assessment and remediation of contaminated sites.

1.4 TRADITIONAL REMEDIATION METHODS AND POTENTIAL NEGATIVE EFFECTS

When soil or groundwater contamination or both are present, a number of remediation options may be considered. With respect to soil contamination, the most common traditional practice has been excavation. Impacted soils are removed from the subsurface, at which point they are commonly transported from the contaminated site, where they may be appropriately disposed. With respect to groundwater, pump-and-treat has been traditionally applied as a remediation measure. Contaminated groundwater is extracted from the subsurface, and following treatment, it is either discharged to a sewer system, applied at the surface, or reinjected into the subsurface. More details regarding these methods as well as several evolving and innovative technologies are presented in Chapter 3.

Although excavation and pump-and-treat may be effectively applied when considering a range of variables and circumstances, they do have technical limitations. With excavation, impacted soil often cannot feasibly be reached, either due to depth or the presence of surface obstructions. Pump-and-treat, while typically effective at removing free-phase contamination, often becomes less effective, and commonly cost-prohibitive, at later stages when removal efficiency decreases. Further, both remediation techniques exhibit unfavorable side effects during application. When considering excavation, the heavy equipment utilized during application generates significant air emissions from fuel combustion, increases wear on roadways during transport, and consumes landfill capacity during disposal. Pump-and-treat consumes energy during pumping operations, often generates excessive volumes of extracted groundwater that is often disposed via sewer facilities, and depending on the treatment alternative, may result in air emissions of the generation of solid waste requiring off-site disposal.

The side effects associated with both excavation and pump-and-treat and their impact to the environment may be quantified. It should be noted that such side effects are not limited to only these two remediation methods. All remediation technologies also result in intended or unintended side effects. Under a range of conditions and applications, these technologies may result in side effects and negative impacts to the environment that outweigh the positive aspects of their application. In essence, if not applied appropriately, the environmental harm can outweigh the good.

1.5 WHAT IS SUSTAINABLE REMEDIATION?

During the Brownfields era, significant innovative technological advances were achieved, and the new collaboration between regulatory agencies and project proponents, combined with numerous redevelopment programs and fiscal or tax incentives tied to redevelopment, led to remarkable projects that satisfied the dual goals of productive land reuse and protection of the environment. However, while these benefits were being realized, a range of project stakeholders began to take notice of some of the drawbacks that commonly occur during site remediation. Many of the remedial programs were resulting in problems *beyond the fence*; while sites were being remediated, many technologies relied upon contaminant partitioning into another phase.

Often the contamination was not being destroyed or degraded into less harmful components; rather, it was being driven from soils and groundwater but conserved as a gas, liquid, or solid. This resulted in unfavorable air emissions, contaminated extracted groundwater, or appreciable quantities of impacted soils. If uncontrolled, these materials would again impact the environment; otherwise, expensive additional treatment or disposal alternatives would have to be considered.

Additionally, secondary (but significant) effects were occurring. In many cases, significant energy or virgin material inputs have been required to facilitate site remediation, resulting in significant greenhouse gas (GHG) emissions or the diversion of limited resources from other potential uses. In many cases, protracted remediation programs could result in appreciable traffic loading, automotive emissions, and wear and tear to arterial roadways from personnel and materials transportation. These unintended side effects reduced the overall net environmental benefit when considering the overall effects of a site remediation program. In rare instances, these activities produced a negative overall environmental effect. Nevertheless, in an era where increased attention has been paid to carbon footprints, resource use, and emissions, many project stakeholders have begun to look for remedial alternatives that incorporate green and sustainable technologies.

Traditional risk-based site remedial approaches have not always been sustainable because they often do not account for broader environmental impacts such as extraction and the use of natural resources, wastes created, and energy use and related GHG emissions for on- and off-site operations and transportation of equipment and materials. These approaches do not explicitly account for the net environmental benefit when all relevant environmental parameters are considered. To address this, principles of *green remediation* and *sustainable remediation* have emerged. There is no industrywide consensus on the definitions of these terms. In general, there are many definitions for sustainability, and a U.S. Federal Executive Order under NEPA defined it as "to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations" (E.O.13514 2009; NEPA 1969). *Sustainable remediation* is defined as a remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of limited resources (Ellis and Hadley 2009). On the other hand, *green remediation* is defined as the practice of considering all environmental effects of remedy implementation and incorporating options to maximize the net environmental benefit of cleanup actions (U.S. EPA 2008). Green remediation generally implies being friendly or beneficial to the environment, whereas the term *sustainable remediation* reflects a broader and more holistic approach aimed at balancing the impacts and influences of the triple bottom line of sustainability (i.e., environmental, societal, and economic) while protecting human health and the environment.

To emphasize the use of green technologies to achieve sustainability, the term *green and sustainable remediation* (GSR) is also used. GSR is defined as a remedy or combination of remedies whose net benefit to human health and the environment is maximized through the judicious use of resources and the selection of remedies that consider how the community, global society, and the environment would benefit, or be adversely affected by, RI and corrective actions (ITRC 2011). GSR is a holistic approach that protects human health and the environment while minimizing environmental side effects. The goals of GSR include (1) minimizing total energy use and promoting the use of renewable energy for operations and transportation, (2) preserving natural resources, (3) minimizing waste generation while maximizing materials recycling, and (4) maximizing future reuse options for remediated land (U.S. EPA 2008; Ellis and Hadley

2009). In addition to the environment, GSR attempts to maximize social and economic benefits (often all known as the triple bottom line) associated with a remedial project. It should be noted that GSR options should be considered throughout the site remediation process during the planning of each of the primary phases: site investigation, FS and response action plan, remedial design, remedial action implementation or construction, remedial action operations and maintenance (O&M), remedial process optimization, and site closure.

Recent governmental actions in the United States have the impetus for increased focus on green and sustainable issues. For instance, in October 2009, President Obama signed an Executive Order that set sustainability goals for Federal agencies and focused on making improvements in their environmental, energy, and economic performance, including requirements that federal agencies set a 2020 GHG emissions reduction target, increase energy efficiency, reduce fleet petroleum consumption, conserve water, reduce waste, support sustainable communities, and leverage Federal purchasing power to promote environmentally responsible products and technologies (White House Press Release 2009). As a responsible agency for the environmental remediation technologies, the U.S. EPA is focused on green aspects (environmental sustainability) of the GSR because several economic and societal aspects of sustainable remediation may not be enforceable under the current CERCLA remedy selection criteria, and thus may not be applicable to NPL, NPL equivalent, and federal facility sites. Hence, an applicable regulatory environment also plays a major role in developing and implementing GSR projects. The Recent National Research Council study also recommended incorporating sustainability in the decision makings of the U.S. EPA, including environmental remediation (NRC 2011).

1.6 SCOPE OF THIS BOOK

Many textbooks have been written that describe environmental remediation in great detail. Additionally, much work has been developed in the past several years pertaining to sustainability. The purpose of this book is to bring these two important concepts together and discuss the evolving study of sustainable remediation. In addition to the overview of environmental concerns, regulation, characterization, and risk-based decision making, an overview of existing environmental remediation technologies is presented. Then, a comprehensive overview of sustainability decision frameworks, metrics, and assessment tools is presented.

This is followed by discussion and analysis of several field applications and case studies with respect to sustainability and the degree of success achieved with each of the respective studies. Finally, an outlook for the future evolution of this innovative approach to environmental remediation is presented.

CHAPTER 2

CONTAMINATED SITE REMEDIATION: GENERAL APPROACH

2.1 EVOLUTION OF CONTAMINATED SITE REMEDIATION

As explained in Chapter 1, the Comprehensive Environmental Response, Compensation, and Liabilities Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA) significantly changed the environmental regulatory landscape. For the first time, these landmark regulations induced compliance with intended waste disposal objectives. Additionally, responsible parties and landowners were compelled to remediate contaminated sites that posed a threat to human health and the environment. However, with such rapid change came significant drawbacks and problems. The regulatory frameworks did not fully address indemnification to truly innocent parties. As such, perceptions about potential liability with respect to properties became a significant barrier to land transactions involving properties with confirmed or perceived contamination issues. Further, cleanup standards had not evolved with the passage of the legislation. Cleanup standards were motivated by an objective to restore contaminated soils and groundwater to a pristine condition. These cleanup objectives greatly affected the magnitude of cleanup effort required for site closure—with the same effect on related costs and time to closure.

Further complicating the situation, the cleanup objectives were often misguided. In many cases, these desired end goals were unnecessary, and the restored soil and water resources could not be functionally used. For instance, it is impractical to remediate groundwater such that contaminants of concern (COCs) are reduced to drinking water standards in areas where groundwater is not considered potable due to naturally occurring conditions. Additionally, it is equally misguided to mitigate contaminant concentrations within soils to nondetectable concentrations at ongoing industrial facilities. As a result, significant resources and time were often expended with little incremental benefit. While CERCLA and RCRA were significantly beneficial in protecting and remediating the environment, a better approach was needed to more efficiently remedy these issues.

As human health and ecological risk assessments became important in feasibility evaluations, the U.S. Environmental Protection Agency (U.S. EPA) developed comprehensive methods to perform these assessments for superfund sites (U.S. EPA 1997). As a result, remediation programs are commonly based on the findings of a risk assessment. The use of a risk-based remedial approach allows for a realistic consideration of exposure pathways, the characteristics of the contamination present at a site as well as the profile of likely future land users, and considerations of the long-term productive development potential of a site. For instance, an abandoned industrial facility would be remediated differently if the site zoning were to remain industrial than if it were to be rezoned for a residential use. In the case of a residential setting, cleanup goals would likely be far more restrictive than if the site were intended to remain for industrial use. As a result, an appropriate site-specific remediation program can be developed and implemented following this risk-based approach to achieve cleanup goals compatible and appropriate for future land use.

A systematic approach is necessary for the characterization and remediation of contamination in order to facilitate the land redevelopment and reutilization process and avoid undue delays. The most important tasks of such a systematic approach include: (1) site characterization, (2) risk assessment, and (3) the selection of an effective remedial action. Figure 2.1 outlines one such systematic approach. Innovative integration of various tasks can often lead to a faster, cost-effective remedial program.

2.2 SITE CHARACTERIZATION

Site characterization is often the first step in leading to a contaminated site remediation strategy. It consists of the collection and assessment of data representing the contaminant type and distribution at a site under investigation. The results of a site characterization form the basis for risk assessment and decisions concerning the requirements of remedial action. Additionally, the results serve as a guide for design, implementation, and monitoring of the remedial system.

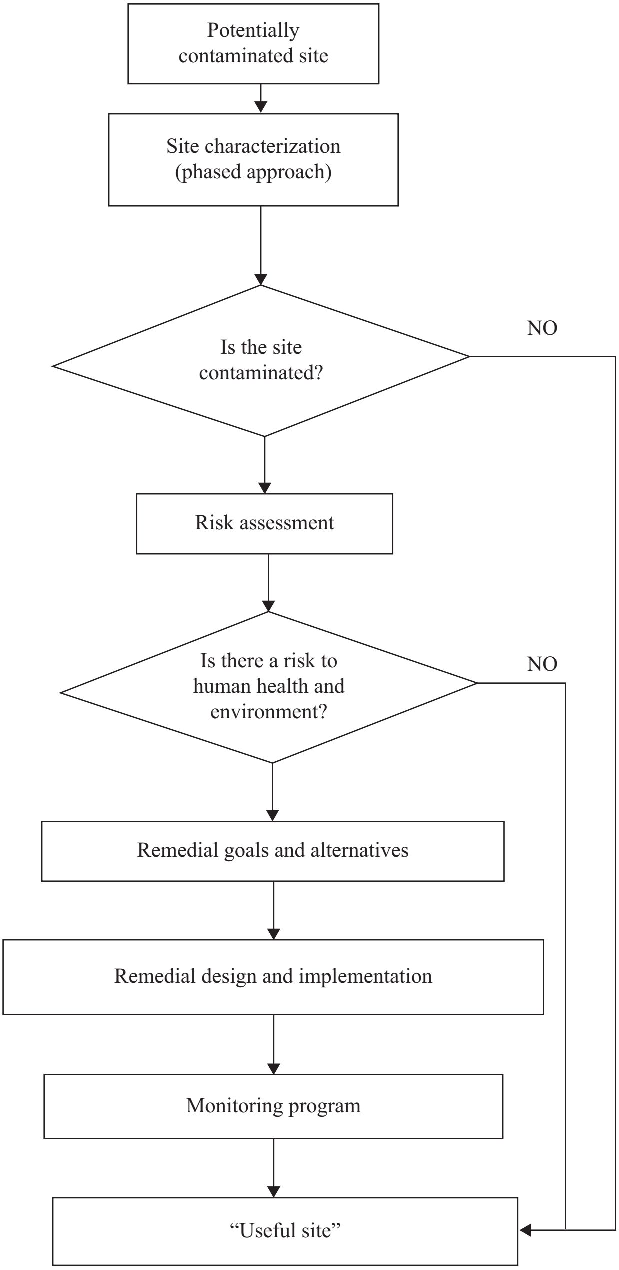

Figure 2.1. General approach for contaminated site assessment and remediation.

Source: Sharma and Reddy (2004).

Each site is unique; therefore, site characterization must be tailored to meet site-specific requirements. An inadequate site characterization may lead to the collection of unnecessary or misleading data, technical misjudgment affecting the cost and duration of possible remedial action, or extensive contamination problems resulting from inadequate or inappropriate remedial action. If not designed and implemented correctly, site characterization can evolve into an expensive and lengthy process, so it is advantageous to follow an effective site characterization strategy to optimize efficiency and cost.

An effective site characterization includes the collection of data pertaining to (1) site geologic data, including site stratigraphy and important geologic formations; (2) hydrogeologic data, including major water-bearing formations and their hydraulic properties; and (3) site contamination data, including type, concentration, phase, and distribution, which include the lateral and vertical extent. Additionally, surface conditions both at and around the site must be taken into consideration.

Because little information regarding a particular site is often known at the beginning of an investigation, it is often advantageous to follow a phased approach for site characterization. A phased approach may also minimize the financial impact by improving the planning of the investigation and ensuring the collection of relevant data. The first phase consists of the definition of investigation purpose and the performance of a preliminary site assessment. This may include a formal phase I environmental site assessment. The purpose of a phase I site assessment, which typically is performed in accordance with the American Society for Testing and Materials (ASTM) Standard 1527 as well as the U.S. EPA All Appropriate Inquiry (AAI) rule, is to determine if recognized environmental conditions (RECs) may exist at the site. In essence, an REC is the potential or confirmed condition or presence of environmental contamination at a site that would affect future beneficial land use. A phase I environmental site assessment includes a review of past practices; historic information; geographical location; regional geologic, hydrogeologic, and topographic information; a review of potential on-site and off-site sources of contamination pertaining to the site; interviews of key site managers and others with knowledge of past and present activities and conditions at the site as well as those who commissioned the study; reconnaissance of the site and adjacent properties; site ownership history; a review of legal deed and titles, including any deed restrictions or activity use limitations (AULs); and other key information that may be useful in determining if RECs exist at the site. Additionally, the phase I assessment may be coupled with other activities, including limited surface and subsurface sampling of potentially affected media. With the exception of limited environmental sampling, the activities associated with a phase I environmental site assessment are noninvasive and would be mostly classified as *literature review* activities.

Based on the results of the phase I site assessment activities, and with the assumption that the phase I assessment has identified the potential presence of RECs at the site, the purpose and scope of the phase II assessment may be developed. While a phase I environmental site assessment is mostly noninvasive, a phase II assessment generally consists of invasive exploration activities. It typically consists of exploratory subsurface investigations, which commonly include a combination of sampling and testing of soil, groundwater, and soil gas. If contamination was detected at the site during the course of limited sampling that may have been performed during the phase I assessment, the phase II assessment would consist of more extensive sampling and testing to confirm the nature and extent of environmental contamination at the site. This may include sampling of the same media (e.g., soil), or other media (groundwater and soil gas) if more extensive impact has been hypothesized. If the phase I assessment did not include sampling but RECs are suspected, an exploratory program would be developed based on the findings and the suspected type of contamination and impacted media. In either case, a detailed work plan should be prepared for the site investigations describing the scope of related field and laboratory testing. The work plan should provide details about sampling and testing procedures, sampling locations and frequency, a quality assurance and quality control (QA/QC) plan, a safety and health (S&H) plan, a work schedule, and a cost assessment.

Depending on the logistics of the project, site characterization may require regulatory compliance and approval or both at different stages of the investigation. Thus, it is important to review the applicable regulations during the preliminary site assessment (phase I). Meetings with regulatory officials may also be beneficial to insure that investigation procedures and results conform to regulatory standards. This proactive approach may prevent delays in obtaining the required regulatory permits and approvals.

Based on the findings of the phase II assessment, additional exploration work may be necessary. Depending on the size, accessibility, and proposed future purpose of the site, this investigation may last anywhere from a few weeks to a few years. Because of the time and effort required, this phase of the investigation is very costly. Additional phases of site characterization must be performed until all pertinent data has been collected.

Ultimately, the goal of the phase II assessment is to develop a comprehensive, meaningful conceptual site model (CSM). Figure 2.2 shows an

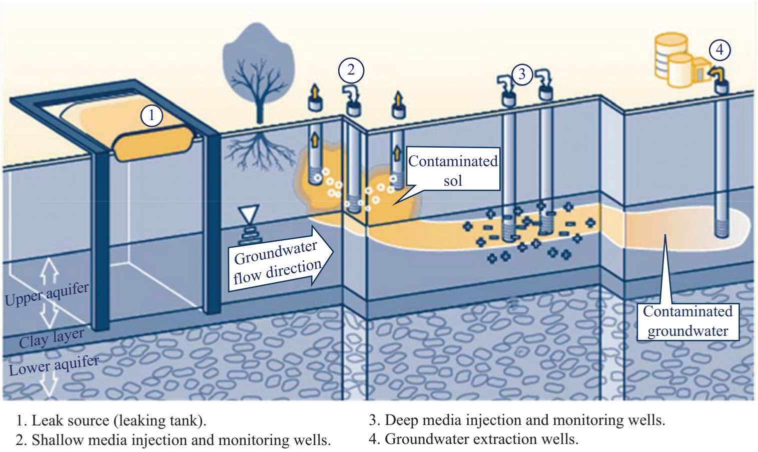

Figure 2.2. Graphical CSM.

Source: U.S. EPA (2010).

example of a CSM. The detailed site investigation activities are performed in order to define site geology, hydrogeology, and the contamination profile. Data obtained from the detailed investigation must be adequate to properly assess the risk posed at the site as well as allow for effective designs of possible remedial systems. The CSM combines all of these as well as the potential for receptors (i.e., humans and aspects of the greater environment) to be exposed to or be impacted by the presence of the contamination. The CSM therefore presents a three-dimensional model of the surface, subsurface, and how receptors may be affected by these conditions within both the surface and subsurface.

For a long time, site characterization methods were basic and direct. Typically, soil impacts were characterized through the collection of soil samples from soil borings. Rotary soil borings, while effective, generate a relatively large volume of soil cuttings; in many cases, these soils may be impacted and require special handling and disposal provisions. Monitoring wells installed using rotary borings also generate significant cuttings and can be expensive and time-consuming to install, develop, and ultimately decommission. Both of these characterization techniques are still widely used today; however, many improved techniques have been developed to improve production, ease construction, or limit the amount of waste materials.

Direct hydraulic-push methods have offered a significant improvement over the use of rotary drilling equipment. Comparable depths of exploration may be reached in most soil conditions. The direct-push technologies commonly utilize small-diameter sampling equipment, greatly reducing the volume of investigation-derived waste (IDW). Additionally, many of these technologies also allow for the recovery of continuous soil cores, which allow for a comprehensive visual viewing of soil lithology and allows for better in-field decisions regarding sample collection for laboratory analysis.

Direct-push technologies have also been useful for groundwater sample collection. Prepacked wells or screened casing may be easily driven to the desired sampling depth, allowing for quality groundwater sample recovery in a cost-effective and time-effective manner as compared to traditional well installation. Well points and casing can also easily be extracted, and the resulting boreholes can be backfilled efficiently following sampling.

Yet another advance has been the rapid evolution and adoption of soil vapor sampling technology. The use of soil vapor sampling has increased dramatically in the past few years, due to both the introduction of more robust sampling technologies and procedures as well as increased favor of the use of soil vapor data in risk assessment.

Previous estimates of soil vapor exposure were calculated using models to estimate volatilization, attenuation, and intrusion into enclosed spaces (e.g., the Johnson and Ettinger Model [1991]). Additionally, ambient air sampling using passive collection vessels were commonly used. However, some began to question the application of various factors and their appropriateness in numerical modeling, and passive sampling has also been questioned because of difficulties in eliminating background sources of interference. Additionally, the increased incremental improvements of sampling equipment (soil vapor wells, direct push equipment, air-tight sampling collection equipment and vessels), and leak detection procedures (e.g., positive pressure sampling environments using inert tracer gases) continue to facilitate the improved quality and reliability of soil vapor data.

Innovative site characterization techniques are increasingly being used to collect relevant data in an efficient and cost-effective manner. Recent advances in cone penetrometer and sensor technology have enabled contaminated sites to be rapidly characterized using vehicle-mounted direct push probes. Probes are available for directly measuring contaminant concentrations in situ, in addition to measuring standard stratigraphic data, to provide flexible, real-time analysis. The probes can also be reconfigured to expedite the collection of soil, groundwater, and soil gas samples for subsequent laboratory analysis.

The membrane interface probe (MIP) is a semiquantitative, field-screening device that can detect volatile organic compounds (VOCs) in soil and sediment (U.S. EPA CLU-IN 2011b). It is used in conjunction with a direct push platform (DPP), such as a cone penetrometer testing (CPT) rig or a rig that uses a hydraulic or pneumatic hammer to drive the MIP to the depth of interest to collect samples of vaporized compounds. The probe captures the vapor sample, and a carrier gas transports the sample to the surface for analysis by a variety of field or laboratory analytical methods. Additional sensors may be added to the probe to facilitate soil logging and identify contaminant concentrations (U.S. EPA CLU-IN 2011b, 2011c).

MIP technology is capable of sampling VOC and some semivolatile organic compounds from subsurface soil in the vadose and saturated zones. It is typically used to characterize hydrocarbon or solvent contamination. Essentially, it provides real-time, semiquantitative data of subsurface conditions, reducing the need to collect soil and groundwater samples as well as the costs and lead times associated with sampling and analysis. It is especially efficient at locating source zones or *hot spots* associated with dense nonaqueous phase liquid (DNAPL) and light nonaqueous phase liquid (LNAPL); this allows for targeted follow-up sampling to precisely determine the contamination constituency and concentration.

Noninvasive, geophysical techniques such as ground-penetrating radar, cross-well radar, electrical resistance tomography, vertical induction profiling, and high-resolution seismic reflection produce computer-generated images of subsurface geological conditions and are qualitative at best. Other approaches such as chemical tracers are used to identify and quantify contaminated zones, based on their affinity for a particular contaminant and the measured change in tracer concentration between wells employing a combination of conservative and partitioning tracers.

Another continuing innovation is the use of mobile analytical laboratories. Although off-site, fixed-base laboratories continue to be popular and necessary for a range of analyses, mobile laboratories are also becoming increasingly popular. With the lab *inside the fence*, confirmation sampling can be conducted in real-time as remediation activities are taking place. This allows the technical professional to make decisions in the field as the activity is occurring, eliminating the need for downtime awaiting results as well as costly remobilization of equipment.

As important as the development of characterization techniques was the development of sampling and analytical methods for soil and water samples. The U.S. EPA developed publication SW-846, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*. This guide compiled analytical and sampling methods evaluated and approved for use in complying with RCRA regulations. SW-846 functions primarily as a guidance document that establishes acceptable sampling and analysis methods. SW-846 was first issued by U.S. EPA in 1980. New editions have been issued to accommodate advances in analytical instrumentation and techniques.

2.3 RISK ASSESSMENT

Once site contamination has been confirmed through the course of a thorough site characterization, a risk assessment is performed. A risk assessment, also known as an impact assessment, is a systematic evaluation used to determine the potential risk posed by the detected contamination to human health and the environment under the present and possible future conditions. If the risk assessment reveals that an unacceptable risk exists due to the contamination, a remedial strategy is developed to assess the problem. If corrective action is deemed necessary, the risk assessment will assist in the development of remedial strategies and goals necessary to reduce the potential risks posed at the site.

The U.S. EPA and the ASTM have developed comprehensive risk assessment procedures. The U.S. EPA procedure was originally developed by the U.S. Academy of Sciences in 1983. It was adopted with modifications by the U.S. EPA for use in superfund feasibility studies and RCRA corrective measure studies (U.S. EPA 1989). This procedure provides a general, comprehensive approach for performing risk assessments at contaminated sites. It consists of four steps: (1) hazard identification, (2) exposure assessment, (3) toxicity assessment, and (4) risk characterization. The most critical aspect of such assessment is developing the CSM, identifying receptors and exposure pathways, and determining exposure dosages under existing and potential remedial conditions. Knowing the toxicology data, risk is quantified, and risk less than 1×10^{-6} (one in one million) is generally considered acceptable. Unfortunately, this assessment is cumbersome and requires a large set of input data or necessity to make assumptions.

The ASTM Standard E1739-95, known as the Guide for Risk-Based Corrective Action (RBCA), is a tiered assessment originally developed to help assess sites that contained leaking underground storage tanks containing petroleum (ASTM 2010). Although the standard is geared toward such sites, many regulatory agencies use a slightly modified version for non-UST sites. This approach integrates risk and exposure assessment practices with site assessment activities and the selection of the remediation technique. The RBCA process allows corrective action activities to be tailored for site-specific conditions and risks and assures that the chosen course of action will protect both human health and the environment.

Different risk assessment methodologies have been developed by various state agencies that are based on tiered approach but applicable to any type of contamination (Sharma and Reddy 2004). The state regulatory agency should be contacted for additional information on such methodologies.

2.4 REMEDIAL ACTION

When the results of a risk assessment reveal that a site does not pose risks to human health or the environment, no remedial action is required. In some cases, however, monitoring of a site may be required to validate the results of the risk assessment. Corrective action is required when risks posed by the site are deemed unacceptable. When action is required, a remedial strategy must be developed to insure that the intended remedial method complies with all technological, economic, and regulatory considerations.

The costs and benefits of various remedial alternatives are often weighed by comparing the flexibility, compatibility, speed, and cost of each method. A remedial method must be flexible in its application to ensure that it is adaptable to site-specific soil and groundwater characteristics. The selected method must be able to address site contamination while offering compatibility with the geology and hydrogeology of the site.

Many other interrelated factors affect the selection and implementation of remedial action, including the following:

- End-use of the site: The proposed future use of the site after the site has been remediated will dictate the need for remediation and the cleanup levels.
- Cost of cleanup: The cost of remediation depends on the site conditions and applicable regulations. The more stringent the regulations, the higher the cost of the remediation.
- Health and safety: Federal regulations require stringent safety measures at contaminated sites. These regulations include Occupational Health and Safety Administration (OSHA) requirements stipulated in 29 CFR 1910.120: Protection of Workers in Hazardous Waste Operations. State regulations also require stringent safety measures. A site-specific health and safety plan is prepared and strictly

followed. All persons who work at the site or who visit the site are required to follow the safety measures.

- Environmental liability: Who is responsible for contamination and who will pay for the remediation are contentious questions to answer. CERCLA uses the court system to assign specific liability for the cleanup of contaminated sites. CERCLA defines four classes of *potentially responsible parties*: (1) the current owner or operator of the site, (2) any person who formerly owned or operated the site at the time of disposal of any hazardous waste, (3) any person who arranged for disposal or treatment of hazardous waste at the site, and (4) any transporter of hazardous waste to the site. This implies that almost anyone involved with the site is a potentially responsible party and liable for the cost of cleanup.

Generally, remediation methods are divided into two categories: in situ remediation methods and ex situ remediation methods. In situ methods treat contaminated soils and groundwater in place, eliminating the need to excavate the contaminated soils and extract groundwater. In situ methods are advantageous because they are less expensive, cause less site disturbance, and they provide increased safety to both the on-site workers and the general public within the vicinity of the remedial project. Successful implementation of in situ methods requires a thorough understanding of the subsurface conditions. In situ containment, using bottom barriers, vertical walls, and caps, may be a feasible strategy to minimize the risk posed by the contamination at some sites. Ex situ methods are used to treat excavated soils and extracted groundwater. Surface treatment may be performed either on-site or off-site, depending on site-specific conditions. Ex situ treatment methods are attractive because consideration does not need be given to subsurface conditions. Ex situ treatment also offers easier control and monitoring during remedial activity implementation. Specific remediation technologies are discussed in detail in Chapter 3.

2.5 SUMMARY

Many sites have been contaminated due to improper waste disposal practices and accidental spills. Due to a lack of environmental laws and regulations, such contaminated sites continued to increase. However, after the promulgation of RCRA and CERCLA, the number of contaminated sites has reduced and efforts have been initiated to clean up all of the contaminated sites. An earlier remedial approach aimed to restore the sites to pristine conditions, which was realized to be impractical. So much time and resources have been expended, yet the problem of contaminated sites persisted.

New and rational approach to the remediation of contaminated sites was then developed. It includes site characterization, followed by risk assessment. If the risk to human health or surrounding ecology is unacceptable, remedial action is required. Several options exist for the remediation of contaminated soils and groundwater, ranging from ex situ and in situ technologies and in situ containment. Remedial action is selected based on the site-specific conditions and remedial goals.

CHAPTER 3

CONTAMINATED SITE REMEDIATION TECHNOLOGIES

3.1 INTRODUCTION

Remedial technologies are classified into two groups based on their scope of application: (1) vadose zone or soil remediation technologies and (2) saturated zone or groundwater remediation technologies. The vadose zone is the geological profile extending from the ground surface to the upper surface of the principal water-bearing formation. In very general terms, it is often simpler to remove the vadose zone impact as compared to saturated zone impacts, and the financial impact of the remediation program may be substantially reduced if the source of pollution is identified and remediated while it is still in the vadose zone, before the onset of groundwater contamination. A number of remedial technologies are suitable for vadose zone (or soil) treatment; however, many of these options are not capable of treating contaminated groundwater. In the case of saturated zone (groundwater) contamination, other technologies must be considered for possible implementation. In some situations, containment technologies may be considered as an interim remedial measure or as the only choice of remediation. To properly remediate subsurface contamination, it is essential to understand the operation, applicability, advantages, and drawbacks of available subsurface remedial and containment technologies. Having this background, one can identify potential sustainable technologies. This chapter provides a brief description of various soil and groundwater remediation technologies and pollution containment technologies and finally identifies which technologies have the potential to be sustainable technologies.

3.2 VADOSE ZONE (SOIL) REMEDIATION TECHNOLOGIES

A major concern at contaminated sites is the possibility of vadose zone contamination that has the potential to infiltrate the underlying groundwater resources. Fortunately, remediation may be implemented within the vadose zone before the onset of contaminant migration into the saturated soil profile and groundwater. The most common practice used to remediate vadose zone contamination is excavation. Simply stated, contaminated soils are removed from the subsurface until clean excavation bases and sidewalls have been established. Impacted soil is typically characterized through subsequent testing, allowing for appropriate transportation and disposal measures, commonly involving landfill disposal. Following excavation activities, clean fill materials are used to backfill the resulting excavation. The contaminated soil may either be treated or untreated before disposal. This approach is simple, easy to perform, fast, and cost effective for small sites. Additionally, it is an applicable method for a wide range of contaminant conditions. Regulatory approval and permits are relatively easy to obtain for excavation. However, the cost effectiveness of excavation diminishes when applied to larger contaminated sites. Additionally, when the contamination extends deeper into the soil profile, excavation becomes very expensive. Because of the costs associated with the excavation, transportation, treatment, and disposal of contaminated soil, excavation is best applied to small, shallow contaminated soils.

When the excavation of contaminated soils is not a feasible option, a number of conventional and innovative treatment methods may be utilized. These methods may either be in situ or ex situ methods. Common remedial methods are summarized in Figure 3.1. Table 3.1 offers a comparative assessment of the different ex situ remedial methods, while Table 3.2 compares several in situ technologies. A brief description of the most popular remedial technologies is provided in the following sections, and the reader should refer to Sharma and Reddy (2004) for more detailed information.

3.2.1 SOIL VAPOR EXTRACTION

Soil vapor extraction (SVE) has proven to be a popular and successful innovative treatment technique for the remediation of vadose zone contamination, particularly volatile organic compounds (VOCs) and motor fuels. An SVE system consists of three basic components: an extraction system, an air flow system, and an off-gas treatment system. By applying

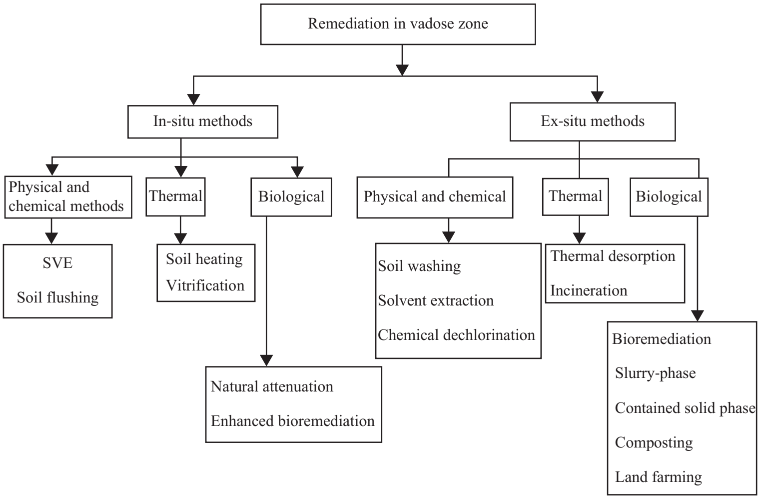

Figure 3.1. Vadose zone (soil) remediation technologies.

a vacuum to the subsurface within the contaminant zone, the extraction system induces the movement of volatile organics and facilitates their removal and collection. Collected vapors pass through the air flow system and are delivered to the off-gas treatment system, or, if regulatory limits permit, are emitted directly to the atmosphere. SVE systems are relatively easy to install, operate, and maintain, and they are easily integrated with other remedial technologies for remediation projects.

3.2.2 SOIL FLUSHING AND SOIL WASHING

In situ soil flushing involves the extraction of contaminants from the soil using water or other selected aqueous wash solutions. The flushing agent may be introduced into the subsurface in a number of ways, and once introduced, the agent moves downward through the contaminant zone. Once the migrating agent or contaminant solution encounters the water table, it will mix with the groundwater, flow down-gradient to a withdrawal point, and be extracted, often via conventional extraction wells. Soil flushing is most effective in soils with hydraulic conductivities equal to or greater than 10^{-3} cm/s. Additionally, the presence of organic matter or clay may hinder contaminant removal due to adsorption. Target contaminants for this technology include light aliphatic and aromatic hydrocarbons. When using soil flushing, however, caution must be used to prevent the transformation products of the extractants and contaminants from adding to the contamination problem.

Table 3.1. Comparative assessment of ex situ soil remedial technologies

Technology	Applicability	Strengths	Limitations	Cost range ($)	Commercial availability
Soil washing	~ Organic compounds ~ Metals ~ Radionuclides	~ Volume reduction	~ Soils with fines greater than 20%	100–300/ton	Widespread
Solvent extraction	~ Organic compounds	~ Wide range of contaminants	~ Clays	100–500/ton	Limited
Chemical dechlorination	~ Chlorinated organic compounds	~ Reduces toxicity; can be used with other technologies	~ Sites with inorganic pollutants	300–500/ton	Limited
Electrokinetics	~ Metals ~ Organic compounds ~ Radionuclides	~ Low K soils ~ Mixed contaminants	~ Metallic objects	90–130/ton	Very limited
Thermal desorption	~ VOCs	~ Lower cost than incineration	~ Clays, aggregated soils with rock fragments	74–184/ton	Widespread
Incineration	~ Organic compounds	~ Wide range of contaminants	~ High cost	500–1,500/ton	Widespread
Vitrification	~ Organic compounds ~ Metals ~ Radionuclides	~ Mixed contaminants	~ High cost ~ Usefulness of end product ~ Long-term integrity	90–700/ton	Very limited
Bioremediation	~ Organic compounds	~ Simple, cost effective ~ Contaminant destruction	~ Control of environmental factors	27–310/ton	Widespread
Solidification and stabilization	~ Metals ~ Organic compounds	~ Proven technology ~ Wide range of contaminants	~ Organic soils ~ Volume increase ~ Long-term integrity	50–250/ton	Widespread

Table 3.2. Comparative assessment of in situ soil remediation technologies

Technology	Applicability	Strengths	Limitations	Cost range ($)	Commercial availability	Complementary technologies
SVE	~ VOCs	~ Proven technology	~ Heterogeneous and low K soils	<100/ton	Widespread	~ Fracturing ~ Heating ~ Horizontal wells
Soil flushing	~ Diesel and crude oil ~ Metals	~ Residual contaminant reduction	~ Trapped flushing solution ~ Low K soils	80–165/cu. yd	Very limited	~ Fracturing ~ Horizontal wells
Electrokinetics	~ Metals ~ Organic compounds ~ Radionuclides	~ Low K soils ~ Mixed contaminants	~ Metallic objects	90–130/ton	Very limited	~ Fracturing ~ Heating ~ Horizontal wells
Bioremediation	~ Organic compounds	~ Conversion into nonhazardous substance ~ Low cost	~ Lengthy treatment times ~ Low K soils	27–310/ton	Widespread	~ Fracturing ~ Horizontal wells
Soil heating	~ Gasoline and diesel	~ Improved hydrocarbon recovery	~ Metallic objects ~ Low K layers in stratified soils	50–100/ton	Limited	~ Fracturing ~ SVE ~ Horizontal wells
Vitrification	~ Organic compounds ~ Metals ~ Radionuclides	~ Mixed contaminants	~ Converts soil into glassy structure ~ Metallic objects	350–900/ton	Limited	~ Fracturing ~ Horizontal wells
Solidification and stabilization	~ Metals ~ Organic compounds	~ Proven technology	~ Low K soils ~ Long-term integrity	100–150/cu. yd	Widespread	~ Fracturing ~ Horizontal wells
Phytoremediation	~ Metals ~ Organic compounds ~ Radionuclides	~ Less secondary waste ~ Broad range of contaminants	~ Limited to shallow depths and low conc. levels ~ Lengthy treatment time ~ Food chain contamination	<100/ton	Very limited	~ Bioremediation

While soil flushing is an in situ technique, soil washing is an ex situ technique. Used in the same manner as its in situ counterpart, soil washing is effective in treating both organic and inorganic compounds, yet it may not be successful in treating clayey or silty soils.

3.2.3 CHEMICAL OXIDATION

Chemical oxidation technologies have also evolved as a preferred remedial alternative for in situ or ex situ remediation of soils and groundwater. With this technology, an oxidizing agent is introduced and mixed into the subsurface. Chemical oxidation typically involves reduction–oxidation (redox) reactions that chemically convert hazardous contaminants to nonhazardous or less toxic compounds that are more stable, less mobile, or inert. Redox reactions involve the transfer of electrons from one compound to another. Specifically, one reactant is oxidized (loses electrons) and one is reduced (gains electrons). The oxidizing agents most commonly used for the treatment of hazardous contaminants in soil are ozone, hydrogen peroxide, hypochlorites, chlorine, chlorine dioxide, potassium permanganate, persulfate, and Fenton's reagent (hydrogen peroxide and iron) (U.S. EPA CLU-IN 2011a). The effectiveness of some of these oxidants can be enhanced through activation (Fenton's reagent, activated persulfate) and used in conjunction with other oxidants (perozone) (ITRC 2005).

3.2.4 SOLIDIFICATION AND STABILIZATION

Another rapid technology is soil stabilization and solidification. With this method, additives or processes are applied to contaminated soil to chemically bind and immobilize contaminants, preventing mobility. This process aims to physically bind contaminants to a stabilized mass. A mixing reagent, commonly Portland cement, is mixed with moist soil and allowed to harden. The final product is a stable mass with very low permeability and good erosion resistance. It is applicable to both heavy metals and to high-molecular-weight organics. The process may be applied in situ or ex situ. When performed ex situ, the treated soil mass may be replaced into the subsurface or off-hauled for disposal at an appropriate landfilling facility. In either in situ or ex situ, it is critical to assure that the reagent has been thoroughly mixed with the soil mass.

Stabilization and solidification has several benefits, including low costs due to the wide availability of inexpensive reagents and additives, a wide range of applicability to varying soil types and contaminant conditions, use of readily available equipment, and rapid application and production rates. Alternatively, some of the drawbacks include the ongoing presence of contamination (although fixated and immobilized), increased volume of impacted material due to the introduction of additives or reagents, potential emissions, especially when VOCs are present in the subsurface, assurance of proper delivery and mixing, and long-term presence may affect potential future site use. Additionally, long-term performance issues have not been fully explored.

3.2.5 ELECTROKINETICS

Electrokinetics, a remediation technique that involves the application of a low electric potential gradient across a contaminated soil zone in order to induce contaminant movement, offers significant potential for the in situ remediation of fine-grained soils. The mass flux of contaminants transported during electrokinetics depends upon the transient geochemistry that takes place under the influence of the induced electrical field. Electrode conditioning procedures are sometimes necessary to induce favorable geochemistry, resulting in greater remediation efficiency. Electrokinetics is suitable for treating clays contaminated with heavy metals, radionuclides, and organic contaminants; often, these contaminants may be removed with efficiencies from 75 to 95 percent.

3.2.6 BIOREMEDIATION

Bioremediation is an increasingly popular technique during which microorganisms are utilized to biologically degrade contaminants into harmless end products. Bioremediation offers flexibility because it may be performed in an in situ or an ex situ manner to address either vadose zone or saturated zone contamination. There are two approaches to bioremediation: one associated with natural attenuation processes (when monitored, this is called monitored natural attenuation [MNA]) and enhanced bioremediation. MNA utilizes naturally occurring microorganisms commonly present within vadose zone soils to degrade organic contaminants. When natural subsurface biological and nutrient conditions are not conducive for remediation, the subsurface may be enhanced to allow degradation to occur through the addition of nutrients, electron donors and acceptors, or suitable microorganisms (bioaugmentation). Whether natural or enhanced bioremediation is utilized, the effectiveness of treatment depends upon the type of contaminant(s), the microbial population, and the physical and chemical conditions in the subsurface. Thus, a careful assessment regarding biological, nutrient, and other environmental conditions (e.g., pH, moisture, temperature) must be performed. Additionally, full mineralization of the contaminants must be assured, as incomplete degradation may often lead to end products that are more harmful than the original contaminants.

3.2.7 THERMAL METHODS

Various thermal methods may be employed to accomplish contaminant remediation. In situ vitrification (ISV) employs electrical power to heat and melt contaminated soil. Organic contaminants are destroyed through pyrolysis, while volatile metals may evolve in off-gases, necessitating off-gas treatment. Vitrification is applicable for soils contaminated with heavy metals, organic contaminants with high sorption coefficients, and radioactive materials. However, effectiveness is reduced in soils with high organic matter, high moisture content, or soils containing large metallic objects (e.g., pipes or drums).

As an alternative, in situ soil heating decontaminates soils through vaporization, steam distillation, and stripping, and may be performed through powerline frequency heating (PLH) or radiofrequency heating (RFH). In situ soil heating is applicable to both organic and semiorganic contamination; however, it may become cost-prohibitive when applied to deep-contaminated sites.

A number of ex situ thermal methods are also effective in treating a variety of contaminants. In addition to ex situ vitrification, incineration is also an ex situ remedial option. Incineration accomplishes destruction through combustion. Incineration may be used to treat all types of organic contaminants at a very high level of efficiency, but the extreme temperatures required for incineration makes it a very expensive technique. When the remedial goal is to increase contaminant removal through volatilization instead of destruction, thermal desorption may be used. During the use of this technique, volatized contaminants, most suitably VOCs or chlorinated solvents, are transported out of the soil. This method is effective in treating volatile contaminants over a wide range of moisture contents, but it may become cost-prohibitive for treating large volumes of contaminated soil.

3.3 SATURATED ZONE (GROUNDWATER) REMEDIATION TECHNOLOGIES

If groundwater contamination is confirmed and corrective action is deemed necessary following a thorough site characterization and risk assessment, one of many remedial technologies may be utilized for corrective action. Some of the aforementioned remedial technologies may be applied to saturated soils, including soil flushing, electrokinetics, and bioremediation. In addition, other popular remedial methods that can be used include: (1) pump-and-treat, (2) air sparging, (3) dual phase extraction, and (4) permeable reactive barriers (PRBs). Actual remedial methods are varied in their applications and their limitations; thus, it is essential to evaluate the benefits, drawbacks, and economic impact of each method, as well as the site-specific soil, hydrogeologic, and contaminant conditions. A comparative assessment of several remedial technologies applicable for saturated zone contamination is shown in Table 3.3.

3.3.1 PUMP-AND-TREAT

Until recently, the most conventional method for groundwater remediation has been the pump-and-treat method. With pump-and-treat, free-phase contaminants and contaminated groundwater are pumped directly out of the subsurface. Treatment occurs above ground, and the cleaned groundwater is either discharged into sewer systems or reinjected into the subsurface. As the groundwater is extracted, dissolved contaminant mass is removed, which induces subsequent dissolution of nonaqueous phase liquid (NAPL) contaminant from free-phase sources or those adsorbed to the soil matrix. Pump-and-treat systems have been operated at numerous sites for many years. Unfortunately, data collected from these sites reveals that although pump-and-treat may be successful during the initial stages of implementation, performance drastically decreases at later times. As a result, significant amounts of residual contamination can remain, unaffected by continued treatment. Due to these limitations, the pump-and-treat method is now primarily used for free product recovery and to control contaminant plume migration.

3.3.2 AIR SPARGING

Air sparging, also known as biosparging, is an established remediation technology useful in the treatment of volatile organic contaminants. During the implementation of air sparging, a gas, usually air, is injected into the saturated soil zone below the lowest known level of contamination. Due to the effect of buoyancy, the injected air will rise toward the surface. As the air comes into contact with the contamination, it will, through a variety of mechanisms, strip the contaminant away or assist in situ degradation. Eventually, the contaminant-laden air encounters the

Table 3.3. Comparative assessment of groundwater remedial technologies

Technology	Applicability	Strengths	Limitations	Cost range ($)	Commercial availability	Complementary technologies
Pump-and-treat	~ Free product recovery	~ Proven technology	~ Residual contamination	Variable	Widespread	~ Fracturing ~ Horizontal wells
Dual phase extraction	~ Organic compounds (LNAPLs)	~ Simple ~ Cost-effective	~ Emulsions ~ Biofouling of wells ~ Residual contamination ~ Heterogeneous and low K soils	3–10/gal. of groundwater	Widespread	~ Bioventing ~ Fracturing ~ Horizontal wells
Air sparging	~ VOCs	~ Simple ~ Cost-effective	~ Heterogeneous and low K soils	<3/gal. of groundwater	Widespread	~ SVE ~ Bioventing ~ Horizontal wells ~ Heating
Flushing	~ Organic compounds ~ Metals ~ Radionuclides	~ Wide range of contaminants	~ Lengthy remediation time ~ Heterogeneous and low K soils ~ Residual flushing agents	80–165/cu. yd. soil	Very limited	~ Pump-and-treat ~ Bioremediation

Bioremediation	~ Organic compounds	~ Mineralization of contaminants ~ Low cost	~ Lengthy remediation time ~ Heterogeneous and low K soils	66–123/cu. yd. soil	Widespread	~ Fracturing ~ Heating ~ Horizontal wells
Reactive walls	~ Organic compounds ~ Metals ~ Radionuclides	~ Low operation and maintenance	~ Subsurface hydrogeology ~ Lengthy remediation time ~ Long-term performance	250–800/L/min.	Limited	~ Fracturing ~ Horizontal wells
Immobilization	~ Metals ~ Radionuclides	~ Cost-effective	~ Heterogeneous and low K soils ~ Long-term performance	100–150/cu. yd. soil	Limited	~ Fracturing ~ Horizontal wells
Electrokinetics	~ Organic compounds ~ Metals ~ Radionuclides	~ Low K soils ~ Mixed contaminants ~ Cost-effective	~ Metallic objects	90–130/ton	Very limited	~ Fracturing ~ Horizontal wells

vadose zone, where it is often collected using a SVE system and treated on-site. Air sparging offers the best results when it is applied to relatively permeable and homogeneous soils. Impermeable soils as well as heterogeneity impact air flow patterns and thus may adversely affect performance. Remediation times using air sparging are much lower than those achieved using other methods. Additionally, since the required equipment is readily available, air sparging is often an economically attractive remedial choice.

3.3.3 DUAL-PHASE EXTRACTION

Dual-phase extraction, also known as vacuum-enhanced recovery, is a hybrid remediation technique that combines technology from pump-and-treat and SVE. During implementation, groundwater is extracted to ground level through the application of a vacuum, allowing for the removal of the dissolved contaminants within the extracted groundwater as well as the contaminant vapors due to the applied vacuum. Both the dissolved and vaporized contaminant may be treated on-site. The cleaned water may be discharged into sewer systems, streams, or reinjected into the subsurface, while the clean air is generally emitted into the atmosphere. Two types of dual-phase extraction are commonly used: single-pump systems and double-pump systems. Dual-phase extraction systems are simple to implement, inexpensive, and well-suited for aquifers with low permeability.

3.3.4 PERMEABLE REACTIVE BARRIERS

PRBs incorporate a reactive media to adsorb, degrade, or destroy contamination within groundwater as it passes through the barrier. Common reactants include zero-valent iron, zeolites, organobentonites, and hydroxyapatite. PRBs may be continuously installed perpendicular to a migrating plume, or they may consist of a *funnel-and-gate* design that diverts water flow through a treatment zone. PRBs must be monitored closely to ensure that suitable reactant mass is present as well as confirm that flow has not been lessened by clogging.

PRBs are also a technology where a mass flux and discharge analysis approach can be an effective analysis alternative. In contrast to the *point* approach utilized with numerous characterization and remediation technologies, the mass flux and discharge approach assesses the transport of contaminant mass across a monitoring interface over a period of time. It can be applied with pumping tests, in-well meters, or integrative approaches, such as the transect method. It can be especially useful in addressing plume stability and fate and transport assessment.

3.4 CONTAINMENT TECHNOLOGIES

In some cases, it may be impractical or undesirable to actively remediate contamination in soils and groundwater via in situ methods. This can be due to the presence of surface obstructions, such as structures or utilities, or the presence of contamination with extent and depth that cannot be readily addressed. In such situations, containment systems may be considered (Figure 3.2). Often times, these are used with institutional controls, such as deed restrictions or activity use limitations (AULs) that can formally notify property stakeholders of the presence of contamination and conditions in which the containment strategies need to be preserved. Containment methods may also be used as interim measures prior to the final selection and implementation of a remedial method.

3.4.1 SURFACE CAPPING

Surface capping involves the installation of a surface barrier that prevents or limits the ability of underlying contaminated subsurface media to be encountered (Figure 3.2a). This may consist of hardscape paving, a synthetic membrane, or natural material soil liner (i.e., a clay liner). In some cases, the presence of a structure may be utilized in that contamination is limited to within a building footprint. Warning devices, such as geogrid, metallic mesh, fabric, or other similar material may be incorporated into the underlying soil to alert future excavations from advancing in these areas of prohibited or limited excavation activity.

3.4.2 SOIL VAPOR MITIGATION SYSTEMS

When soil and groundwater are impacted with volatile contaminants, such as solvents or lighter-phase petroleum hydrocarbons, land users can be threatened by exposure to contaminated indoor air emanating from the subsurface. This potential exposure can be mitigated through the use of a soil vapor barrier and venting system. A vapor barrier consists of a membrane placed immediately below foundation elements and floor slabs. The membrane, often some type of polymer and either placed in sheeting or sprayed in place, provides a nearly impermeable break that minimizes the

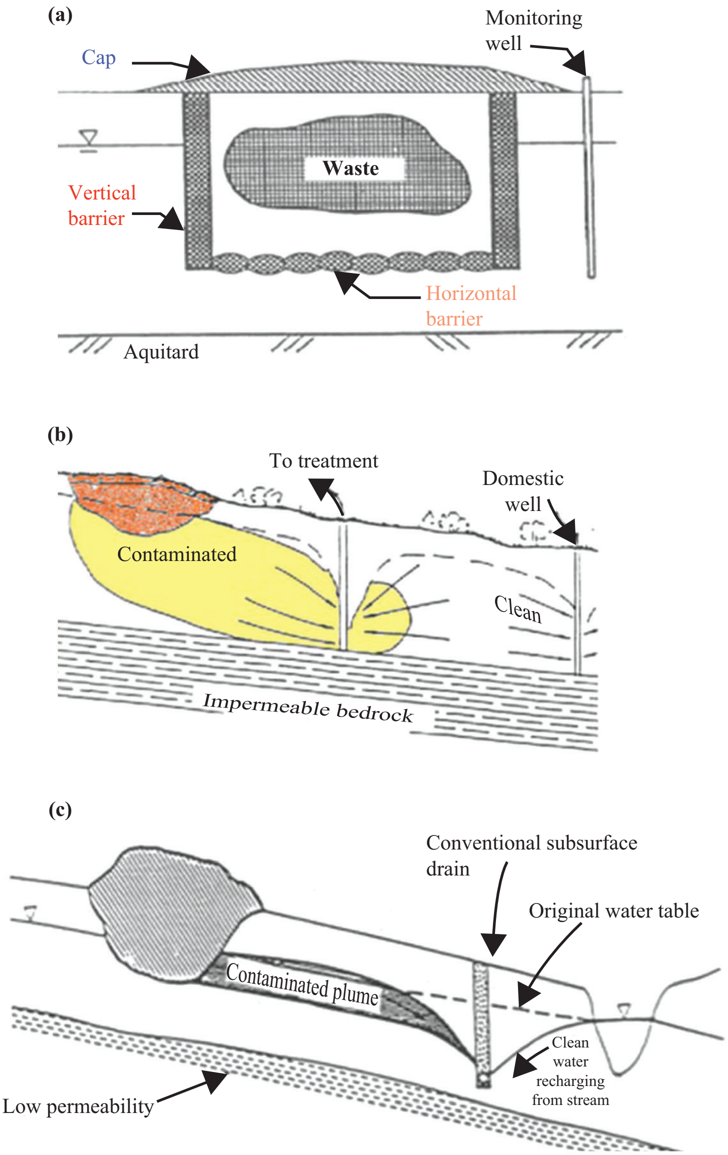

Figure 3.2. Containment technologies: (a) cap, vertical barrier, and bottom barrier; (b) pumping well systems; and (c) subsurface drain system.

Source: Sharma and Reddy (2004).

potential for contaminant vapors from migrating into a structure. Often times, these systems are combined with passive or active ventilation systems. Passive ventilation systems typically consist of a low-profile intake pipe network connected to a manifold system, which is in turn vented to the atmosphere. The slight induced pressure gradient due to atmospheric venting will induce the flow of the collected vapors for harmless discharge to the atmosphere. In some cases, the systems are outfitted with active controls, such as compressors or fans, to induce greater venting and flow.

3.4.3 VERTICAL AND BOTTOM BARRIERS

Vertical barriers are also known as vertical cutoff barriers, vertical cutoff walls, or simply barrier walls, and they function in the subsurface to contain contaminants (Figure 3.2a). Usually vertical barriers are embedded or keyed into a low permeability formation. Horizontal configuration can be circumferential, down-gradient, or up-gradient. With circumferential configuration, the vertical barrier completely surrounds the contamination, hence considered to be the most effective option. Different types of vertical barriers have been developed and the most common ones are: slurry trench barriers, grouted barriers, mixed-in-place barriers, and steel sheet pile barriers. Slurry trench barriers are extensively used and they are constructed by excavating a narrow trench (two to four feet wide). As excavation proceeds, the trench is filled with slurry that stabilizes the walls of the trench, thereby preventing collapse. The trench is finally backfilled with soil-bentonite backfill or cement-bentonite backfill. The backfill may be amended with selected materials such as activated carbon or zeolite to improve contaminant containment.

If the vertical barrier is keyed into the low permeability formation, there is no need for providing a bottom barrier. If the low permeability formation is at very deep depth, providing a bottom barrier may become an economical option. The bottom barriers are constructed by using grouting techniques or employing a combination of tunneling, installation of geomembranes, and grout or slurry mix.

3.4.4 PUMPING WELLS AND DRAINS

Groundwater pumping well systems are active containment systems used to manipulate and manage groundwater for the purpose of removing, diverting, and containing a contaminated plume or for adjusting groundwater levels to prevent plume movement (Figure 3.2b). Groundwater pumping wells are frequently used in combination with vertical barriers to prevent groundwater from overtopping the barrier and to minimize the contact of the contaminants with the barrier to prevent barrier degradation. Combinations of extraction of injection wells with appropriate pumping or injection rates are used depending on the site-specific conditions.

Subsurface drains are an alternative to pumping wells for the containment of contaminated groundwater (Figure 3.2c). They consist of drain pipe surrounded by filter and backfill to intercept a plume hydraulically down-gradient and then divert to manholes to collect flow and pump the discharge to a treatment plant. Subsurface drains are best suited for sites where the groundwater table is relatively shallow and the contaminants are near the water table. Unlike pumping systems, operation and maintenance costs associated with subsurface drains are low.

3.5 INTEGRATED REMEDIATION TECHNOLOGIES

Using just one technology may not be adequate to remediate some contaminated sites when different types of contaminants exist (e.g., heavy metals combined with VOCs) or when the contaminants are present within a complex geological environment (e.g., a heterogeneous soil profile consisting of lenses or layers of low permeability zones surrounded by high permeability soils). Under these situations, different remediation technologies can be used sequentially to achieve the remedial goals. The use of such multiple remediation technologies is often referred to as *treatment trains*. Typical treatment trains used at contaminated sites include soil flushing followed by bioremediation, SVE followed by soil flushing, SVE followed by stabilization and solidification, and thermal desorption followed by solidification and stabilization, which is then followed by soil flushing. Alternatively, different remediation technologies can be used concurrently, such as SVE and air sparging, electrokinetics and bioremediation, and soil flushing and bioremediation.

3.6 POTENTIAL SUSTAINABLE REMEDIATION TECHNOLOGIES

When analyzing potential remedial technologies for a remedial program, the key principles and factors of sustainable remediation should be incorporated at all phases, including (1) site investigation; (2) remediation system selection, design, construction, and operation; (3) monitoring; and

(4) site closure and determination of appropriate future land use. The use of the U.S. EPA's Triad decision-making approach is highly recommended for site investigations (U.S. EPA 2001). This method consists of three interrelated components: (1) systematic project planning, (2) dynamic work strategies, and (3) real-time measurement technologies to reduce decision uncertainty and increase project efficiency. Appropriate sustainability principles can be incorporated into site characterization activities. For example, direct push technologies, geophysical techniques, and passive sampling and monitoring techniques can reduce waste generation, consume less energy, and minimize land and ecosystem disturbance.

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

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

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

A variety of remedial technologies satisfy core sustainable remediation criteria; however, the project life cycle for a specific technology should be considered to determine if it is appropriate for use at a given site. For example, ex situ biological soil treatment is considered a promising sustainable remediation technology; however, the impacts of transporting soil (if off site treatment is required) should be evaluated. Similarly, enhanced in situ bioremediation is also considered an attractive sustainable remediation technology, but the cumulative impacts that occur during its characteristically long treatment duration should be compared to those of other active remediation that require less time. In general, passive containment systems such as phytoremediation and PRBs utilize little mechanical equipment and minimize energy input while resulting in minimal waste or effluent.

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

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

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

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

3.7 SUMMARY

Over the past two decades, several technologies have been developed to remediate contaminated soils and groundwater. These technologies can be ex situ or in situ technologies, and the applicability and limitations of these technologies should be kept in mind while selecting a remedial option for a contaminated site. These technologies are based on the manipulation of physicochemical, thermal, electrical, and biological processes in the subsurface. In addition to the treatment technologies, containment technologies are also available to serve as interim remedial measures or as sole remedy option. Often, one technology may not be adequate to address the site contamination or economical option; hence, combinations of technologies may be used to address the site contamination in an effective and economical manner. In dealing with sustainable remediation, sustainability principles should be incorporated at all phases of site remediation, starting with site investigation to remedial implementation to site closure. Often, in situ passive and contaminant degradation technologies are considered sustainable technologies, but a combination of active and passive removal and degradation technologies may be needed to achieve the net environmental benefit of site remediation. However, the site-specific conditions and project-specific goals will dictate the selection of remedial technologies.

CHAPTER 4

SUSTAINABLE REMEDIATION FRAMEWORKS

4.1 INTRODUCTION

Chapter 1 introduces the concept of sustainable remediation. As discussed, a sustainable remediation approach serves to address environmental contamination in a manner that provides the best net overall benefit to the project with respect to environmental, economic, and societal dimensions. This is accomplished through the minimization of inputs and energy, preservation of natural resources, minimization of waste generation and by-products for the betterment of the community, and a maximization of future reuse options for the specific land being addressed by the remediation program. Nevertheless, while these parameters should be quantitative and objective, there are subjective concerns that are incorporated into an analysis of the degree of success in addressing these concepts. To address this, several frameworks have been developed to provide methods in which to assess the degree of sustainability with respect to remediation alternatives.

A sustainability framework is a systematic basis by which the sustainability of a remediation project may be assessed with respect to environmental, social, and economic factors. This assists in decision making to evaluate the sustainability metrics of a remediation project. Although a universally acceptable standardized frame has not yet been developed, several agencies and organizations in the United States and other countries have been active in developing frameworks for measuring and facilitating sustainability in remediation of contaminated sites. The frameworks developed by U.S. Environmental Protection Agency (U.S. EPA), Sustainable Remediation Forum (SURF), Interstate Technology & Regulatory Council (ITRC), and American Society of Testing and Materials (ASTM) are explained in this chapter.

4.2 U.S. EPA FRAMEWORK

In 2008, the U.S. EPA developed a framework for incorporating sustainable environmental practices into the remediation of contaminated sites. The framework emphasizes green remediation concepts and techniques that take into consideration a range of environmental effects. In emphasizing green remediation, the goal of the framework is to evaluate and select remediation alternative and options that achieve maximum net environmental benefit during all phases of site characterization, remediation system implementation and operation, and postremediation monitoring.

This framework emphasizes only environmental aspects with respect to sustainability without explicit consideration of social and economic aspects. Therefore, this framework is generally considered a means to achieve green remediation as opposed to sustainable remediation. Green remediation differs from sustainable remediation in that environmental effects and means to maximize net environmental benefit of cleanup actions are solely emphasized. Common concepts of emphasis that are included with the typical remediation goals of protecting public health include consideration of project-generated or secondary impacts such as air pollution, greenhouse gas (GHG) emissions, water consumption, and ecological damage. Other concepts included in the framework are goals to reduce energy consumption and waste generation, and ultimately these contribute to climate change.

The green remediation framework has incorporated five core elements in order to achieve green remediation as shown in Figure 4.1. These core elements are as follows:

1. *Minimization of total energy use with the maximization of renewable energy use*: Remediation alternatives are assessed with respect to their ability to maximize the use of renewable energy while simultaneously minimizing overall energy consumption. To achieve this, project alternatives that use energy-efficient equipment, incorporate onsite renewable resources (e.g., wind, solar), and purchase commercial energy derived from renewable resources are encouraged. Additionally, emphasis is placed on the use of passive-energy technologies and the means to use waste-to-energy techniques.
2. *Minimization of air pollutants and GHG emissions*: Remediation alternatives that reduce total air emissions, including emissions of air pollutants and GHG in all phases of operation, are favored. Activities that emphasize this include equipment operation techniques

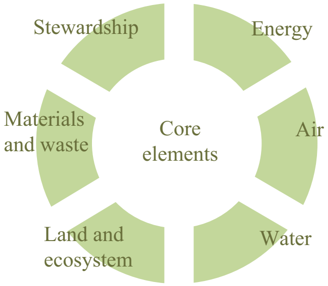

Figure 4.1. Core elements of the U.S. EPA green remediation framework.

Source: U.S. EPA (2008).

that minimize dust generation and transport, dust suppression techniques, including watering and covering, and the use of hybrid engine technologies. Air emissions can also be minimized through the use of low-fuel consumption equipment, transportation fleet modifications such as diesel engine retro-fits, and air flow streamlining on over-the-road tractor-trailer rigs, reduced idling operations, clean fuels, and emissions-controlling devices that reduce GHG, particulates, and dust.

3. *Water conservation and minimization of impacts to water resources*: Remediation alternatives that minimize the use of water and reduce impacts to water resources in all stages of operation are encouraged. Possible methods may include water conservation used in field processes, use of water-efficient products, water capture and reclamation for reuse (e.g., gray water), use of drought-tolerant and water-efficient vegetation in site restoration, and use of effective best management practices (BMPs) for stormwater, erosion, and sedimentation control. These actions can minimize the use of fresh water, maximize water reuse and recycling, and prevent negative impacts to water quality in nearby water resources.
4. *Land and ecosystem protection*: Emphasis is given to remediation alternatives that reduce impacts to the land and ecosystems during all stages of implementation. Some techniques include activities that minimize the remediation activity footprint; limit the disturbance of mature, noninvasive, native vegetation, surface hydrology, soils, and habitats in the cleanup area; reuse of healthy vegetation on- or off-site; and minimize noise and light disturbance.

Impacts can be minimized by incorporating noninvasive, passive, and less-energy intense in situ technologies (e.g., monitored natural attenuation, bioremediation, phytoremediation, evapotranspiration covers, and permeable reactive barriers) and the use of deed restrictions or activity use limitations that promote contaminant avoidance instead of lengthy remediation.

5. *Reduce, reuse, and recycle materials and waste reduction and reusing and recycling of materials*: Emphasis is placed on remediation alternatives that minimize the use of virgin materials and the generation of waste during all stages of implementation as well as maximization of the use of recycled materials. Possible methods may include the use of recycled and locally generated or sourced materials, reusing waste materials (e.g., concrete made with coal combustion products such as fly ash or bottom ash), diversion of construction and demolition debris from disposal using recycling or recovery programs, and the use of rapidly renewable materials.

In addition to the five core elements, the framework also emphasizes actions that promote long-term environmental stewardship. Such goals in advancing large-scale environmental stewardship aim to reduce GHG contributing to climate change, encourage the use of renewable energy systems, incorporate adaptive management approaches for long-term site control, and solicit community involvement from a wide range of project stakeholders (Figure 4.1). Although the stewardship component of the U.S. EPA's initial six core elements was removed during refinement, it remains an encouraged concept through the use of identified actions within EPA programs such as the Office of Solid Waste and Emergency Response (OSWER) Community Engagement Initiative.

The five core elements presented earlier can be quantitatively assessed through the use of environmental footprint analysis. The U.S. EPA has developed a methodology for evaluation; the details of this methodology are presented in Chapter 5.

4.3 SURF FRAMEWORK

In 2009, the SURF published a White Paper that presented the status of sustainable remediation practices and highlighted the need for developing a well-defined framework for incorporating sustainability into remediation projects (Ellis and Hadley 2009). Subsequently in 2011, SURF published a framework that provided a systematic, process-based, holistic approach that practicing professionals can follow for integrating sustainability in all phases of a remediation project, from the project inception to the end use or future use of the site (Holland et al. 2011). The framework does not compromise the need to protect human health through remediation cleanup goals; rather, the framework emphasizes that remediation cleanup and sustainability-based objectives are to be simultaneously pursued and achieved.

The framework consists of a tiered decision-making process that considers each phase of a remediation project: site characterization, remediation alternative analysis and selection, remediation system design and construction, operations and maintenance, postmonitoring, and closure. It allows the use of qualitative and quantitative assessments, ongoing revision of the conceptual site model (CSM) based on assessment results, identification and implementation of sustainability impact measures, and decision making throughout the remediation project to address sustainability. The framework also encourages communication among the project stakeholders who may be affected by the remediation project.

The framework consists of three tiers, similar to that of the ASTM RBCA approach (as explained in Chapter 1):

- Tier 1 consists of standardized, nonproject specific, qualitative evaluations that utilize checklists, lookup tables, guidelines, results from past project experience, rating systems, and matrices to identify BMPs that maximize positive sustainability impacts. Limited stakeholder involvement, if any, is expected in this tier. This tier may especially be emphasized on smaller-scale sites that have time, budget, and resource constraints and in situations where higher-tiered evaluation is not likely to provide appreciable benefit.
- Tier 2 consists of a semiquantitative approach using project-specific and nonproject-specific information as well as greater stakeholder involvement. The project-specific information can be evaluated using various assessment tools such as emission calculations, exposure calculations, scoring and weighing systems, spreadsheet-based tools, and simple cost-benefit analyses. This tier evaluation is best suited for sites that are moderately complex and requires greater involvement of stakeholders.
- Tier 3 is the most comprehensive, detailed, quantitative evaluation for sustainability based on detailed project-specific information. This tier requires a large quantity of project-specific data and utilizes sophisticated tools such as life-cycle assessment (LCA). A greater stakeholder involvement is required in this approach. This tier evaluation is most appropriate for large-scale, long-term remediation projects with a wide range of stakeholders.

A Tier 1 evaluation is recommended as a minimum for any remediation project. With further complexity, the framework is designed to offer flexibility to adapt to any project, and different combinations of tiers may be used for various stages of a remediation project. Overall, the main goal of this framework is to assess the degree of sustainability and incorporate sustainability with any known project inputs, and to allow the design professional to make informed decision with respect to sustainability at each stage of a remediation project.

4.4 ITRC FRAMEWORK

In 2011, ITRC developed a generalized, flexible framework that outlines the planning and implementing processes for integrating environmental, social, and economic considerations in each phase of the green and sustainable remediation (GSR) (ITRC 2011). The framework was tailored for use by U.S. state regulators as well as cross-sector remediation practitioners. Figure 4.2 shows this framework. The GSR planning process consists of five generalized steps that can be performed to user-desired depth during each phase of the project. These steps include the following: (1) evaluation and update of a CSM; (2) establishment of GSR goals for the project; (3) project stakeholder involvement; (4) selection of GSR metrics, evaluation level, and boundaries; and (5) documentation of GSR efforts. This process is flexible and scalable, depending on the size of the project and site-specific conditions. Specifically, the ITRC framework was intended to be equally functional for projects of small-scale, near-term

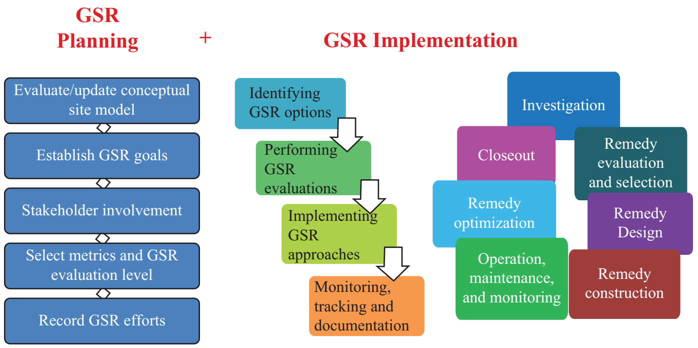

Figure 4.2. ITRC GSR framework.

Source: ITRC (2011).

timeframes and low-budget constraints as well as projects of large-scale, long-term timeframes and high-budget complexity.

As discussed in this book, the CSM incorporates a wide range of surface and subsurface information and facilitates decision making that is required for executing the remediation project. The CSM assesses how contamination has been dispersed within the environment and how soil and groundwater conditions may impact its fate and transport. The CSM also incorporates the built environment and allows for consideration of potential human and ecological receptors as well as the likely exposure scenarios for these receptors. Because the CSM forms the basis for defining and implementing an effective overall strategy for the site, it should evolve throughout the life cycle of the cleanup project. Some examples of relevant GSR information that may be incorporated include on-site or nearby areas of ecological significance, on-site beneficial reuse of groundwater, air emissions and pollutant sources, on-site renewable energy, community assets on or adjacent to the site (e.g., green space), and non-impacted soil reuse.

Establishing goals is a key element of GSR planning, and GSR goals should be developed early during the planning process. GSR goals can be influenced by a number of factors, including corporate and regulatory sustainability objectives, stakeholder requirements, responses to a regulatory policy, or stakeholder response to a desire to lower the potential impacts from a project and make it more sustainable. The GSR goals may include the five core elements of U.S. EPA green remediation. Additionally, a wide range of project-specific criteria may be incorporated, including technologies that minimize energy consumption, alternatives that emphasize returns with respect to social and economic considerations, incorporation of renewable energy sources or recycled or repurposed materials, characterization and postremediation monitoring activities that minimize the generation of investigation-derived waste, and optimization of construction and remediation system operation that enhances aesthetic considerations such as noise and dust.

Stakeholder involvement begins with identifying all applicable stakeholders. Stakeholders can be identified by *mapping* a project's area of influence or impact to determine what groups, areas, or activities could be affected by the planned work. Stakeholders may include federal, state, or local regulators, local governments, future site owners or site users, the site owner or operator, responsible parties, local residents affected by a site, the general community, local businesses that may benefit directly or indirectly from the remediation project, and site contractors. While GSR measurables and goals can serve to optimize potential collateral impacts, such as GHG emissions, water consumption, waste generation, traffic, and noise, it is essential that all project stakeholders acknowledge that the overarching objective of the cleanup action is to protect human health and the environment. At no point in the GSR framework application should the practitioner preclude the onus of cleanup with any aspect of the GSR evaluation and implementation. In short, the GSR evaluation and implementation are not reasons for *doing nothing*.

For each of the GSR goals identified, appropriate metrics are considered and selected to assess, track, or evaluate those goals. Metrics may be objective or subjective. Objective GSR metrics may include GHG emissions, energy consumption, recycling and waste minimization, and resource consumption. Subjective metrics may include beneficial reuse of property, job creation and preservation, and creation of community assets (e.g., parkland or open space created, habitat created, or preserved). A three-level approach is recommended for evaluating and selecting GSR metrics:

- Level 1 consists of *common-sense*-based BMPs. These are selected to promote resource conservation and process efficiency. The net impact on the environment, community, or economics is not evaluated with this approach. Although quantitative results may be tracked to demonstrate a monetary return on investment for the employment of certain BMPs (e.g., simple documentation of dollar and fuel savings for efficient trip routing and anti-idling policies).
- Level 2 consists of the selection and implementation of BMPs at a minimum, *plus* some degree of qualitative and semiquantitative evaluation. Qualitative evaluations may reflect trade-offs associated with different remedial strategies or use value judgments for different GSR goals to determine the best way to proceed. Semiquantitative evaluations are those that can be completed by use of simple mathematical calculations or intuitive tools (e.g., conversion factors, online calculators, and spreadsheet-based programs).
- Level 3 consists of selection and implementation of BMPs *plus* a comprehensive quantitative evaluation. The evaluation may employ LCA or detailed footprint analysis techniques and tools. Requiring more time and expertise, this level is intended for use by remediation professionals prepared to conduct and document a detailed evaluation. This level of evaluation is likely to be reserved for the mature project site with high stakeholder engagement standards (e.g., a stakeholder charrette).

GSR boundaries should be identified for each GSR evaluation. The GSR boundaries may be defined as the degree to which the GSR evaluation is conducted. A variety of factors influence the boundaries of a GSR evaluation, such as the physical site boundaries to be assessed within the project budgetary constraints and whether life-cycle considerations are to be addressed. The assessment of boundaries considers all the phases of the project, data availability, stakeholder considerations, timing, and budget. The most rigorous (Level 3) approach is to consider a comprehensive cradle-to-grave analysis for all materials used; such an analysis considers all inputs and outputs associated with the materials beginning with the mining or extraction of raw materials to the ultimate disposal or reuse of residuals. In some instances, a less rigorous approach may be appropriately considered; for instance, an analysis may incorporate the direct manufacture of the products consumed during a remediation project but would not consider the impacts of transporting raw materials or energy inputs to the manufacturer. An even less rigorous approach might consider only the impacts of direct inputs and outputs that occur on the site.

The documentation of GSR efforts is a critical part of determining whether or not GSR goals are being achieved at a site. Effective documentation also provides an appropriate and useful means of communicating ongoing benefits and accomplishments to stakeholders. When documenting GSR evaluations, information would ideally include all assumptions, tools, resources, boundary conditions, and other key principles that have been incorporated into the analysis. A greater richness of detail of these aspects is desirable so that the overall approach can be understood and the results can be reproduced and verified. Any constraints or barriers encountered should also be clearly documented.

4.5 ASTM FRAMEWORK

ASTM has developed a standard guide for sustainable remediation specifically focused on *greener* cleanups, in their ASTM E2893 standard. The standard describes a process for identifying, evaluating, and incorporating BMPs and, as appropriate, integrating a quantitative evaluation that facilitates an overall net reduction in environmental impact associated with remediation projects. This guide addresses the five core elements outlined in the U.S. EPA green remediation framework as described in Section 4.2. The standard provides detailed guidance on planning and scoping a remediation project, implementing appropriate BMPs, employing a quantitative evaluation when appropriate, and documenting and reporting of sustainability-related performance.

The BMP evaluation process describes steps for identifying, prioritizing, selecting, and implementing BMPs, whereas the quantitative evaluation describes a more detailed assessment process, which may include an environmental footprint analysis or LCA. The BMP evaluation process relies on professional judgment to prioritize and select activities that will likely reduce the environmental footprint. The quantitative evaluation relies on appropriately selected system boundaries and estimated data inputs to quantify anticipated environmental footprint reductions prior to implementing BMPs. The BMP evaluation process, quantitative evaluation, or a combination of the two may be implemented over the entire remediation project cycle or at one or more project phases as shown in Figure 4.3.

The E2893 standard provides a comprehensive list of greener cleanup BMPs as shown in Table 4.1. Applicable BMPs to a specific project should be organized and prioritized to optimize appropriate selection and implementation for a project with due consideration of cost and benefits associated with the remediation project. These BMPs are organized into the following categories: (1) project planning and team management, (2) sampling and analysis, (3) materials, (4) vehicles and equipment, (5) site preparation and land restoration, (6) buildings, (7) power and fuel, (8) surface water and stormwater, (9) residual solid and liquid waste, and (10) wastewater. Additional BMPs, if deemed necessary, can also be identified and implemented, depending on the site conditions, to further reduce the environmental footprint of the remediation project.

A quantitative evaluation may also be performed to assist in the selection of appropriate BMPs. This evaluation calculates the environmental footprint at each phase of the remediation project with consideration of the five U.S. EPA core elements. Similar to LCA-type evaluations, this evaluation should consist of seven steps:

1. *Goal and scope definition*: Identification of the scope of the evaluation and the desired parameters to be addressed.
2. *Boundary definition*: Establishment of the physical and time-related boundaries to be incorporated into the study, including the specific activity or activities to be assessed.
3. *Core elements and contributors to the core elements*: Identification of the core elements that will be evaluated in the study, as well as the key contributors to the core elements.
4. *Collection and organization of information*: Development of a methodical system in which pertinent data and information will be collected and organized such that it may be appropriately evaluated.

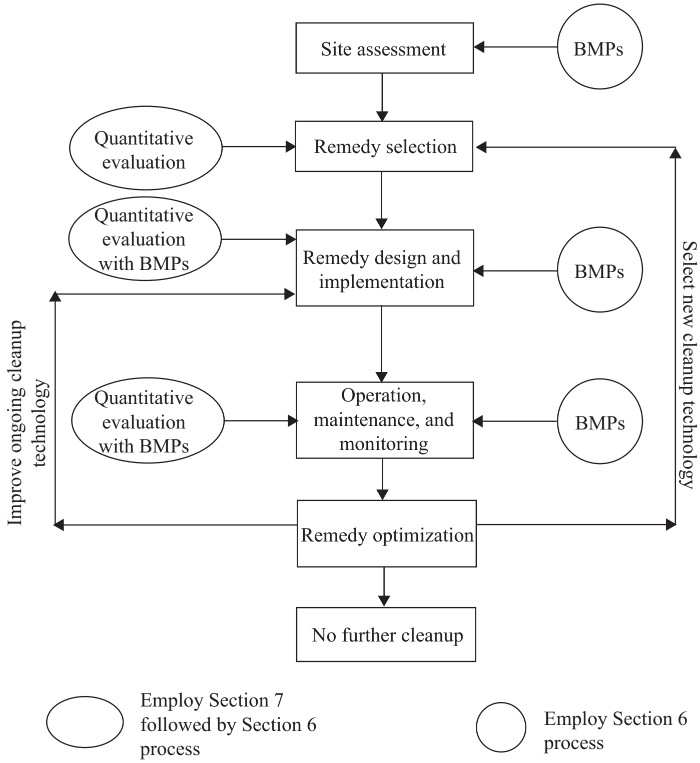

Figure 4.3. ASTM greener cleanup overview.[1]

[1]Sections refer to sections in the standard guide ASTM E2893

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5. *Calculations for quantitative evaluation*: Selection of an appropriate calculation mechanism, such as an environmental footprint analysis or LCA, for data evaluation.
6. *Sensitivity and uncertainty analyses*: Appropriate sensitivity and uncertainty analyses for the calculation and evaluation.
7. *Documentation*: Recording of appropriate findings and conclusions so that appropriate recommendations may be made for the remediation project such that overall environmental benefit is optimized. These results may then be used to select appropriate BMPs for the project.

Similar to the U.S. EPA framework, the ASTM E2893 standard only addresses green aspects of remediation projects. Other sustainable

Table 4.1. ASTM Greener Cleanup BMPs

Category	BMP	Core element addressed (at Site Level)					Remediation technology										
		Energy	Air	Water	Materials and waste	Land and ecosystems	Soil vapor extraction	Air sparing	Pump and treat	In-situ chemical oxidation	Bioremediation/MNA	In-situ thermal treatment (ISTT)	Phytotechnology	Subsurface containment & treatment barriers	Excavation and surface restoration	Ex-situ bio/chemical oxidation	Vapor intrusion mitigation
Buildings	Minimize the size of the housing for aboveground treatment system and equipment	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
Buildings	Install energy recovery ventilators in buildings to allow incoming fresh air while capturing energy from outgoing, conditioned air and destratification fans to better circulate warmer air indoors during colder months	X	X				X	X	X	X	X	X		X	X		

Buildings	Reuse existing structures for treatment system, storage, sample management and so on.	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Buildings	Build energy efficient heating and cooling into new buildings by using natural conditions such as prevailing wind directions for cooling and heating, photovoltaic/passive solar	X					X	X	X	X	X	X		X	X	X	X
Buildings	Use non *natural conditions* methods for energy conservation (for example, choosing Energy Star qualified boilers or heat pumps)	X					X	X	X	X	X	X		X	X	X	X
Buildings	Design energy efficient Heating, Ventilation, and Air Conditioning (HVAC) systems (for example, programmable heating and coding systems) or establish separate heating/cooling zones	X					X	X	X	X	X	X		X	X	X	X
Buildings	Institute a process for using demand-response mechanisms to reduce use of electricity while responding to power grid needs	X					X	X	X	X	X	X		X	X	X	X

Buildings	Properly insulate/reinsulate buildings and use green insulation materials (for example, spray-on cellulose)	X			X		X	X	X	X	X	X		X	X	X	X
Buildings	Build energy efficiency lighting into new buildings by using natural conditions such as passive lighting and by using energy efficient systems such as Energy Star lighting and/or light sensors	X					X	X	X	X	X	X		X	X	X	X
Buildings	Choose water efficient plumbing fixtures (for example, tankless water heaters), and design for use of graywater			X			X	X	X	X	X	X	X	X	X	X	X
Materials	Use recycled content (for example, steel made from recycled metals, concrete or asphalt from recycled crushed concrete and/or asphalt, respectively, and plastic made from recycled plastic; tarps made with recycled or biobased contents instead of virgin petroleum-based contents)				X		X	X	X	X	X	X	X	X	X	X	X

Materials	Use biobased products (for example, erosion control fabrics containing agricultural byproducts)				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Link a deconstruction project with a replacement construction project (for example, the same site of the deconstruction project or a local current construction or renovation project) to facilitate reuse of clean salvaged materials				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Use on-site or local materials, when possible (for example, wood waste for compost, rocks for drainage control)	X	X		X		X	X	X	X	X	X	X	X	X	X	X
Materials	Steam-clean or use phosphate-free detergents or biodegradable cleaning products instead of organic solvents or acids to decontaminate sampling equipment			X	X	X	X	X	X	X	X	X	X	X	X	X	X

Materials	Use wood-based materials and products that are certified in accordance with the FSC Principles and Criteria for wood building components				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Use regenerated Granular Activated Carbon (GAC) for use in carbon beds				X		X		X			X					X
Materials	Consider preheating vapors (preferably passive) to reduce relative humidity prior to treatment with vapor phase GAC to improve adsorption efficiency if preheating does not produce unacceptable tradeoffs				X		X										X
Materials	Salvage uncontaminated objects and infrastructure with potential recycle, resale, donation, or reuse				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Maximize the reuse of existing wells for sampling, injections or extractions, where appropriate, or design wells for future reuse	X	X		X	X	X	X	X	X	X	X					X

Materials	Implement a flexible network of piping (under or aboveground) which allows for future modular increases or decreases in the extraction or injection rates and treatment modifications	X			X		X	X	X	X	X	X					X
Materials	Use timers or feedback loops and process controls for dosing chemical injections	X	X		X					X	X					X	
Materials	Use in-well downhole real time data collection systems with remote sensing capabilities for monitoring groundwater parameters to optimize injection of oxidants and reagents	X	X		X			X		X	X						
Materials	Use by products, waste, or less refined materials from local sources in place of refined chemicals or materials (for example, cheese whey, molasses, compost, or off-spec food products for inducing anaerobic conditions; limestone in place of concentrated sodium hydroxide)	X	X		X					X	X		X			X	

Materials	Select oxidants or reagents with a lower environmental burden				X	X				X	X					X	
Materials	For biomass substrates (for example, algae-based oils, soybean oil, other waste or by-products from forestry, plant nursery, food processing and retail industries) used during in-situ bioremediation, utilize material from providers that can demonstrate use of sustainable techniques	X	X	X	X	X					X					X	
Materials	For ISTT using Electrical Resistance Heating (ERH), recover and recycle or re-use steel electrodes at project completion				X							X					
Materials	Use plants that can sequester carbon for a long time (several decades)		X			X							X		X		
Materials	Use unwanted vegetation as a source of biofuel	X			X	X							X		X		
Materials	Use plants, amendment, or input that require minimal management and water	X		X	X	X							X		X		

Materials	For reactive component of permeable subsurface treatment barriers, use locally available waste (for example, mulch or compost), by-products (for example, slag), or less-refined materials (for example, apatite, natural zeolites) in place of refined chemicals (for example, zero-valent iron, hydrogen reducing compounds) or materials, where possible, without compromising site-specific performance and longevity goals	X	X		X									X			
Materials	For the nonreactive component of permeable treatment or containment barriers, use locally derived materials (for example, sand or gravel)	X	X		X									X			

Materials	Use waste pozzolans (for example, fly ash, slag) to the maximum extent possible as a component of the stabilizing agent for in-situ soil stabilization or surface cover if allowed under federal and state regulations and suitable testing indicates no contaminant leaching				X									X	X		
Materials	Select plant species (including those used for constructed wetlands) that are compatible with local and regional ecosystems and require minimal water and amendments			X	X	X							X		X		
Materials	Choose geotextile fabric or drainage tubing composed of 100% recycled materials, rather than virgin materials, for lining, erosion control, and drainage on landfill covers				X										X		X
Materials	When installing a rubberized asphalt system for a landfill cover system, substitute a portion of the hot mix asphalt with rubber from recycled tires				X										X		

Materials	For concrete landfill covers, substitute a portion of the Portland cement with concrete made of fly ash or slag if allowed under federal and state regulations and suitable testing indicates no contaminant leaching				X										X		
Materials	Use crushed concrete for biobarriers or capillary breaks instead of natural rock for landfill covers				X	X									X		
Materials	For landfill covers and other plant-based systems, use organic material such as compost instead of chemical fertilizers to amend the soil				X	X							X		X		
Materials	Use local plant stock to minimize transportation and increase acclimation survivability (that is, decrease probability of replanting)	X	X		X	X							X		X		

Materials	Use biodegradable seed matting constructed of recycled materials (for example, paper, saw dust, hay)				X	X							X		X		
Materials	Use pre-existing, native and non-invasive vegetation for phytoremediation or restoration activities				X	X							X		X		
Materials	Do not use synthetic liners if a borehole for deep tree planting remains competent after drilling				X	X							X				
Materials	Select well, heater materials and treatment equipment to facilitate reuse. For example, carbon steel casings may resist chlorine stress corrosion better than stainless steel. Prevent condensation in metal extraction piping via pipe insulation, jacketing, and heat tracing to preserve equipment. Add caustic where needed to minimize acid corrosion of materials and equipment and thereby enhance their longevity				X		X	X	X	X	X	X					

Materials	Consider co-locating electrodes and recovery wells in the same borehole, particularly in the saturated zone, to minimize the total number of wells and land disturbance	X	X	X	X	X						X					
Materials	Use dedicated materials (that is, reuse of sampling equipment and nonuse of disposable materials or equipment) when performing multiple rounds of sampling				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Purchase materials in bulk quantities and packed in reusable or recyclable containers and drums to reduce packaging waste				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Use products, packing material, and equipment that can be reused or recycled				X		X	X	X	X	X	X	X	X	X	X	X
Materials	Prepare, store, and distribute documents electronically using an environmental information management system				X		X	X	X	X	X	X	X	X	X	X	X

Materials	Recycle as much nonusable or spent equipment or materials as possible following completion of project				X		X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Conduct pilot tracer tests to optimize hydraulic delivery of reagents and assure capture of target groundwater zone to be treated aboveground	X			X				X	X	X						
Power and fuel	When possible, operate remediation system during off-peak hours of electrical demand without compromising cleanup progress	X					X	X	X	X		X					
Power and fuel	Use pulsed rather than continuous injections when delivering or extracting air to increase energy efficiency when nearing asymptotic conditions	X					X	X			X						
Power and fuel	Use gravity flow where feasible to reduce the number of pumps for water transfer after subsurface extraction	X			X				X								
Power and fuel	Install amp meters to evaluate consumption rates on a real-time basis to evaluate options for off-peak, energy usage	X					X	X	X	X	X	X					

Power and fuel	Use on-site generated renewable energy (including but not limited to solar photovoltaic, wind turbines, landfill gas, geothermal, biomass combustion, etc.) to fully or partially provide power otherwise achieved through onsite fuel consumption or use of grid electricity	X	X				X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Insulate all applicable pipes and equipment to improve energy efficiency	X					X		X	X	X	X					
Power and fuel	Use heat pumps or solar heating in place of electrical resistive heating when preheated extracted groundwater is required prior to treatment	X							X								
Power and fuel	Use solar power pack system for low-power system demands (for example, security lighting, system telemetry)	X					X	X	X	X	X	X	X	X	X	X	X

Power and fuel	Purchase renewable energy via local utility and Green Energy Programs or renewable energy credits or certificates (RECs or Green tags) to power cleanup activities	X	X				X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Employ auxiliary power units to power cab heating and air conditioning when a machine is not operating (such as SmartWay generator or plug in outlet)	X	X				X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Install a modular renewable energy system that can be used to meet energy demands of multiple activities over the lifespan of the project (for example, powering field equipment, construction or operational activities, supplying energy demands of buildings)	X	X				X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Use gravity flow to introduce amendments or chemical oxidants to the subsurface when high-pressure injection is unnecessary	X			X					X	X					X	

Power and fuel	When nearing asymptotic conditions or when continuous pumping is not needed to contain the plume and reach clean-up objectives, operate pumping equipment in pulsed mode	X					X	X	X	X	X						X
Power and fuel	Capture en-site waste heat (for example, treatment plant effluent, excess plant steam, ground-source heat pumps, mobile waste-to-heat generators, furnaces/air conditioners operating with recycled oil, etc.) to power cleanup activities	X					X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Use biodiesel produced from waste or cellulose-based products, preferring local sources wherever readily available to reduce transportation impacts		X		X		X	X	X	X	X	X	X	X	X	X	X
Power and fuel	Use permanent injection wells for delivery of chemical oxidants if multiple applications are expected	X			X	X				X	X						

Power and fuel	For constructed wetlands, maximize use of gravity flow for conveyance of water	X			X						X		X				
Power and fuel	Use passive sub-slab depressurization system to mitigate vapor intrusion	X															X
Power and fuel	Use no- or low-mowing species between plantings to minimize mowing	X	X										X		X		
Power and fuel	Switch to less energy-intensive technology for remediation polishing when possible (for example, suspend pump and treat or SVE and initiate bioremediation or phytotechnology) when overall energy balance supports the concept	X		X	X	X	X	X	X			X					
Power and fuel	For SEE. use a natural gas-fired boiler rather than a diesel boiler and preheat water delivered to boiler, if possible, using recycled heat from extracted fluids	X										X					
Power and fuel	Insulate the surface of the Target Treatment Zone (TTZ) to reduce energy losses and use greener insulation alternatives	X			X							X					

	such as Light Expanded Clay Aggregate (LECA) beads rather than polyurethane foam																
Power and fuel	Schedule treatment period when groundwater table is lower in order to minimize energy requirements	X										X					
Power and fuel	For ISTT, heat a Chlorinated Volatile Organic Compound (CVOC) DNAPL source zone to the boiling point of water to facilitate steam stripping rather than low-temperature thermal	X										X					
Power and fuel	Use the right ISTT technology tor the hydrogeologic setting. For example: 1. Use SEE for highly transmissive aquifer settings 2. Use electrical heating via Thermal Conduction Heating (TCH) or ERH for moderate to low-permeability settings 3. Consider a combination of SEE and electrical heating for mixed stratigraphy TTZs	X										X					

Power and fuel	If reintroduced water is required during ERH, use recycled hot extracted fluids or steam to maintain electrode temperature	X		X								X					
Power and fuel	For ISTT, conduct comprehensive soil sampling to assure that data used for determining baseline electrical resistivity represent the entire treatment area; for example, wetter soil areas may need lower power inputs than dryer areas in order to propagate an electricity current and meet target temperatures	X										X					
Power and fuel	For ISTT, consider a phased approach that sequentially heats subareas of large sites to reduce equipment needs and identify opportunities for conserving energy and other resources over time	X			X							X					
Power and fuel	Explore the use of natural gas-fired systems that enable in-well combustion of the contaminants and recovery of associated heat, resulting in a lower energy demand	X					X					X					

Power and fuel	Integrate a Combined Heat and Power (CHP) system powered by natural gas or cleaner diesel to generate electricity while capturing waste heat that can be used to condition air inside buildings for vapor treatment or other onsite operations	X					X	X	X			X					
Power and fuel	For ISTT with steam enhanced extraction, choose a water-tube boiler rather than a fire-tube boiler wherever feasible; the smaller tubes in water-tube boilers increase boiler efficiency by allowing more heat transfer from exhaust gases	X										X					
Power and fuel	Install heat recovery equipment such as feedwater economizers or combustion air preheaters to recover and use heat otherwise lost in exhaust gas. For example, in ISTT, use off-gases from a thermal oxidation unit to help heat recycled water for the drip system	X					X		X			X					

Power and fuel	For ISTT with steam enhanced extraction, install solar thermal equipment to preheat boiler feed-water and makeup water to reduce the energy needed for raising water temperatures to the target levels	X										X					
Project planning and team management	Select Facilities with green policies for worker accommodations and periodic meetings	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Project planning and team management	Use local staff (including subcontractors) when possible to minimize resource consumption	X	X		X		X	X	X	X	X	X	X	X	X	X	X
Project planning and team management	Buy carbon offset credits (for example, for airline flights) when in person meetings are required		X				X	X	X	X	X	X	X	X	X	X	X

Project planning and team management	Establish green requirements (for example, Suggested Management Practices (SMPs) end BMPs) as evaluation criteria in the selection of contractors and include language in Request for Proposals (RFPs), Request for Qualifications (RFQs), subcontracts, contracts, and so on.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Project planning and team management	Plant at the optimum time of the season (for example, late winter or early spring) to minimize irrigation requirements and increase acclimation survivability	X		X	X	X							X		X		
Project planning and team management	Develop a contingency plan met maximizes the replanting needs while minimizing re-mobilization	X			X	X							X		X		
Project planning and team management	Surgically treat the TTZ and select appropriate performance standards to minimize volume requiring treatment relative to remedial goals	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

Project planning and team management	Perform a heat and energy balance calculation to optimize heating and extraction rates which require an adequate characterization of site hydraulics and hydrogeology. Maintain the energy balance on a daily basis during operation and adjust extraction strategy accordingly and minimize unnecessary operation period	X										X					
Residual solid and liquid waste	Minimize off-site disposal of solid waste by improving solids dewatering with a filter press or other technologies	X	X		X		X	X	X	X	X	X	X	X	X	X	X
Residual solid and liquid waste	Reuse or recycle recovered product (such as resale of captured petroleum products, precipitated metals, and so on) and materials (for example, cardboard, plastics, asphalt, concrete, etc.)				X				X				X		X		
Residual solid and liquid waste	Use filters (for example, bag or cartridge filters) that can be backwashed to avoid frequent disposal of filters				X		X		X								

Residual solid and liquid waste	Use geotextile bags or nets, to contain excavated sediment, facilitate sediment drying, and increase ease of sediment placement or transport, when appropriate			X		X	X	X	X	X	X	X	X	X	X	X	
Residual solid and liquid waste	Segregate drilling waste based on location and composition to reduce the volume of drilling waste disposed off-site; collect needed analytical data to make on-site reuse decisions	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Residual solid and liquid waste	Use alternative drilling methods including Direct Push Technology (DPT) or sonic technology for well drilling to minimize drill cuttings that require disposal	X	X		X	X	X	X	X	X	X	X					
Residual solid and liquid waste	Provide on-site collection and storage area for compostable materials for use on-site or by the local community				X	X	X	X	X	X	X	X	X	X	X	X	X
Residual solid and liquid waste	Minimize soil excavation during installation of in-situ reactive barriers by using existing excavation, deep soil mixing, injection or other subsurface infrastructure				X	X								X	X		

Sampling and analysis	Use direct sensing noninvasive, technology such as a membrane interface probe, X-ray fluorescence, LIF sensor, CPT, Rapid Optical Screening Tool (ROST), Fuel Fluorescence Detector (FFD), and seismic refraction or reflection	X			X	X	X	X	X	X	X	X	X	X	X	X	X
Sampling and analysis	Use field test kits for screening analysis of soil and groundwater contaminants such as petroleum, polychlorinated biphenyls, pesticides, explosives. and inorganics to minimize the need for offsite laboratory analysis and associated sample packing and shipping	X	X		X		X	X	X	X	X	X	X	X	X	X	X
Sampling and analysis	Use on-site mobile lab or other field analysis (for example, portable gas chromatography or rnass spectrometry for fuel-related compounds and VOCs) to minimize the need for offsite laboratory analysis and associated sample packing and shipping	X	X		X		X	X	X	X	X	X	X	X	X	X	X

Sampling and analysis	Contract a laboratory that uses green practices or chemicals	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sampling and analysis	Use multi port sampling system in monitoring wells to minimize the number of wells needing to be installed				X	X		X	X	X	X	X	X	X			
Sampling and analysis	Use tree core sampling to estimate the source, extent, and age of a contaminant (for example, metals, VOCs, SVOCs) plume	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Sampling and analysis	Use local laboratory to minimize impacts from transportation	X	X				X	X	X	X	X	X	X	X	X	X	X
Sampling and analysis	Use passive and no purge groundwater sampling system			X	X			X	X	X	X	X	X	X			
Sampling and analysis	Use stressed vegetation to locate contaminant hotspots to guide development of sampling and analysis plans and optimize design of monitoring well network	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X

Site preparation or land restoration	Revegetate excavated areas or areas disrupted by equipment or vehicles as quickly as possible using native vegetation, if possible, and restore as close as possible to original conditions			X		X	X	X	X	X	X	X	X	X	X	X	X
Site preparation land restoration	Survey on-site infrastructure to determine material types and approximate quantities that could be reused or recycled and evaluate opportunities for on-site or local reuse or recycling				X	X	X	X	X	X	X	X	X	X	X	X	X
Site preparation land restoration	Minimize use of pesticides through the use of green alternatives (for example, nonchemical solarizing technique) and an integrated pest management plan				X	X									X		
Site preparation or land restoration	Minimize cleaning of trees throughout investigation and cleanup	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X

Site preparation land restoration	Maximize use of native, noninvasive and drought resistant vegetative cover across the site during restoration using a suitable mix of shrubs, grasses, and forbs to preserve biodiversity and related ecosystem services			X		X	X	X	X	X	X	X	X	X	X	X	X
Site preparation or land restoration	Minimize soil compaction and land disturbance during site activities by restricting traffic to confined corridors and protecting ground surfaces with biodegradable covers, were applicable			X		X	X	X	X	X	X	X	X	X	X	X	X
Site preparation or land restoration	Reclaim and stockpile uncontaminated soil for use as fill or other purposes such as frost prevention and erosion control layers in landfill covers				X	X	X	X	X	X	X	X	X	X	X	X	X

Site preparation or land restoration	Salvage uncontaminated and pest- or disease-free organic debris, including trees downed during site clearing, for use as fill, mulch, compost, or habitat creation				X	X	X	X	X	X	X	X	X	X	X	X	X
Site preparation or land restoration	Cover filled excavations with biodegradable fabric to control erosion and serve as a substrate for ecosystems			X	X	X							X	X	X	X	X
Site preparation or land restoration	Enhance existing natural resources, manage surface drainage, prevent soil or sediment runoff and promote carbon sequestration by incorporating wetlands, bioswales, and other types of vegetation into overall remedial approach		X	X		X							X	X	X		
Site preparation or land restoration	Restore and maintain surface water banks in ways that mirror natural conditions			X		X							X		X	X	

Site preparation or land restoration	Use onsite or nearby sources of backfill material for excavated areas, if shown to be free of contaminants	X	X		X		X	X	X	X	X	X	X	X	X	X	X
Site preparation or land restoration	Use onsite uncontaminated sand, gravel, and rocks for drainage within landfill cover	X	X	X	X										X		
Site preparation or land restoration	Use remotely controlled or non-invasive techniques to monitor landfill cover integrity; for example, use open path spectroscopy techniques to periodically confirm no escape of landfill gas	X	X		X										X		X
Site preparation or land restoration	Use horizontal wells to distribute chemicals or additives to optimize delivery of materials and minimize surficial footprint					X				X	X						

Site preparation or land restoration	When canopy closure has reached high percentage (for example, over 75 percent) allow naturalization to occur (that is, do not remove downed trees and branches except for safety and access issues, allow leaf litter to lay to create forest floor providing natural mulching and weed control			X	X	X							X		X		
Site preparation or land restoration	Design systems to allow natural volunteer growth or spreading to fill in entire target area over time (minimize initial planting; fill in over time), if time permits			X	X	X							X		X		
Site preparation or land restoration	Use SmartWay transportation retrofits (for example skirts, air tabs) on tractor-trailers whenever possible	X	X				X	X	X	X	X	X	X	X	X	X	X
Site preparation or land restoration	Use minimum slope while maintaining proper drainage in design of landfills to reduce the volume of fill material required				X	X									X		

Site preparation or land restoration	Use lower permeability soils than required by regulation in landfill cover design when soils are available locally to reduce the amount of leachate generated	X		X	X										X		
Surface and storm water	Install and maintain silt fences and basins to capture sediment runoff along sloped areas			X		X	X	X	X	X	X	X	X	X	X	X	X
Surface and storm water	Use a leachate collection system for a landfarm (along with a leachate treatment system) to fully preserve the quality of downgradient water bodies, soil, and groundwater			X		X					X				X		
Surface and storm water	Use captured rainwater for tasks such as wash water, irrigation, dust control, constructed wetlands, or other uses			X		X	X	X	X	X	X	X	X	X	X	X	X
Surface and storm water	Use excavated areas to serve as retention basins in final storm water control plans			X	X	X	X	X	X	X	X	X	X	X	X	X	X

Surface and storm water	Install a landfarm rain shield (such as a plastic tunnel) with rain barrels or a cistern to capture precipitation for potential onsite use			X						X	X				X	X	
Surface and storm water	Use gravel roads, porous pavement, and separated pervious surfaces rather than impermeable materials to maximize infiltration			X		X	X	X	X	X	X	X	X	X	X	X	X
Surface and storm water	Install earthen berm on landfill covers that utilize on-site or local materials to manage run on and runoff storm water	X	X		X	X							X		X	X	
Surface and storm water	Use subsurface or vertical flow wetlands rather than surface flow wherever possible to minimize alterations to existing land surface conditions or ongoing activities and to allow use of a greater range of plant species			X		X							X				

Vehicles and equipment	Install one-way check valves in well casing to promote barometric pumping (passive SVE) as a polishing step once the bulk of contamination has been removed if venting to atmosphere is acceptable	X					X	X									X
Vehicles and equipment	Use centrifugal blowers, rather than positive displacement blowers and intake air line mufflers, to decrease noise levels					X	X	X									X
Vehicles and equipment	Use variable frequency drive motors to automatically adjust energy use to meet system demand on blowers, vacuum pumps and so on that accommodate changes in operating requirements as treatment progresses	X					X	X	X			X					X

Vehicles and equipment	Use equipment to increase automation such as electronic pressure transducers, thermo-couples, and water quality monitoring devices coupled with an automatic data logger	X	X	X			X	X	X	X	X	X					X
Vehicles and equipment	Use biodegradable hydraulic fluids on hydraulic equipment such as drill rings				X		X	X	X	X	X	X	X	X	X	X	X
Vehicles and equipment	Implement an idle reduction plan	X	X			X	X	X	X	X	X	X	X	X	X	X	
Vehicles and equipment	Minimize diesel emission through the use of retrofitted engines, ultra-low or low sulfur diesel or alternative fuels, or filter/treatment devices to achieve Best Available Control Technology (BACT) or Maximum Achievable Control Technology (MACT)		X				X	X	X	X	X	X	X	X	X	X	X
Vehicles and equipment	Soundproof all aboveground equipment housing to prevent noise disturbance to surrounding environment					X	X	X	X	X		X					X

Vehicles and equipment	Implement a telemetry system to reduce frequency of site visits	X	X				X	X	X	X	X	X	X	X	X	X	X
Vehicles and equipment	Replace conventional vehicles with electric, hybrid, ethanol, or compressed natural gas vehicles	X	X				X	X	X	X	X	X	X	X	X	X	X
Vehicles and equipment	Mix amendments into soil in situ whenever possible to minimize dust generation and emissions		X			X								X	X		
Wastewater	Redirect influx of upgradient groundwater into the treatment area by adding engineering controls (for example, installation of subsurface barriers to divert groundwater)	X		X					X			X		X			

Wastewater	Use seasonal removal (for example, cold or dry) or ground-freezing technologies, if environmentally beneficial, to minimize dewatering prior to excavation	X			X									X	X	X	
Wastewater	Reinject treated groundwater to the subsurface to recharge an aquifer			X					X								
Wastewater	Reclaim clean or treated water from other site activities for use in injection slurries or as injection chase water			X	X		X	X	X	X	X	X		X			
Wastewater	Use treated slurry or process water for other cleanup activities or non-remedial applications such as irrigation or wetlands enhancement			X	X				X		X		X		X	X	
Wastewater	Use dewatering processes that maximize water reuse			X	X									X	X	X	

Wastewater	Treat condensate in onsite systems where contaminant types and concentrations permit rather than have them shipped offsite for treatment	X	X				X	X	X			X					X
Wastewater	Recycle condenser water as a supplemental cooling water where contaminant concentrations permit			X	X		X	X	X			X					X
Wastewater	Treat potentially contaminated purge water with an on-site treatment technique prior to reinjecting into an on-site well of discharge to a storm drain or waterway at permissible	X	X		X			X	X	X	X	X	X	X			
Wastewater	Use uncontaminated wastewater or treated water for tasks such as wash water, irrigation, dust control, constructed wetlands, or other uses			X	X		X	X	X	X	X	X	X	X			

Wastewater	Employ closed-loop graywater washing system for decontamination of trucks			X	X		X	X	X	X	X	X	X	X	X	X	
Wastewater	Consider discharging wastewater to a publicly owned treatment works (POTW) or other regional water treatment plant rather than building and operating an on-site treatment plant, when feasible and environmentally beneficial based on additional analysis	X			X		X	X	X			X					X
Wastewater	Contain and manage concrete washout water to prevent contamination through storm water runoff			X		X	X	X	X	X	X	X		X	X		X

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dimensions, such as those related to social or economic concerns, are not directly addressed. ASTM has developed another standard for sustainable remediation projects, ASTM E2876, which provides a framework for integrating environmental, economic, and social aspects into remediation projects. BMPs implemented under this guide can incorporate all three aspects of sustainability (environmental, economic, and social) into remediation projects that are designed to address human health, public safety, and ecological risks (see Figure 4.4).

The goal of implementing BMPs is to address the sustainable objectives identified for the site. The environmental portions of the guide align with the green remediation core elements established by the U.S. EPA. Socially related BMPs focus on community involvement, the degree of community involvement based on the complexity and size of the site and the remediation project, as well as the relative degree to which the interests of the community are affected by the impacted site and proposed remediation project. A wide range of activities may be used for community engagement. For small, noncomplex sites, community involvement

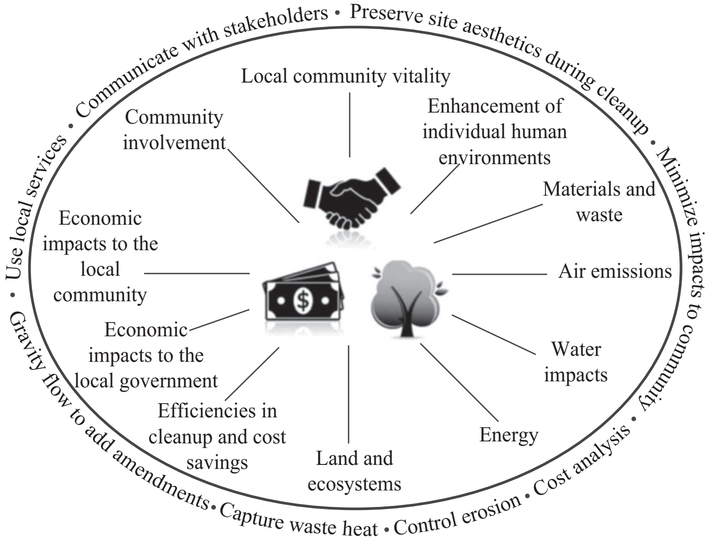

Figure 4.4. ASTM sustainability framework: Relationship between the sustainable aspects (center), core elements (spokes), and some example BMPs (outer rim of wheel).

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activities may include public notices (both electronic and paper mail), site signage, website information, community meetings, radio or television announcements, or distribution of fact sheets about the selection and implementation of sustainable BMPs. At sites with complex activities, or where there is a high level of interest on the part of the community, the level of involvement should be increased. In these circumstances, the user should identify and recruit representatives of key stakeholder groups via local community groups, civic associations, chambers of commerce, homeowners associations, park associations, and clubs. Community leaders may be solicited for involvement through personal invitations, door-to-door communications or introductions, letters, or phone calls. Community leaders and representatives should be encouraged to participate in discussions and decision-making processes. Common goals should be sought between project proponents and stakeholders and directed toward outcomes reflective of the interests of each constituent group and of the community as a whole.

With respect to the economic sustainability dimension, potential economic impacts to the local community, local government should be considered in parallel with potential costs and benefits directly associated with the remediation project, including an emphasis on the maximization of positive public economic impacts to the local community. One means to enhance overall economic impact is through consideration of the economic multiplier effect. The concept is focused on direct local investment that will, in turn, foster secondary economic benefits to the community. For example, the project proponent may choose to utilize local contractors and materials suppliers for the remediation project. In turn, these local businesses will often utilize a significant portion of their benefit into other local businesses, such as service providers (restaurants, gas stations, etc.), as well as local labor pools for temporary or long-term employment. This element could also benefit social aspects by reducing unemployment and increasing on-the-job training and experience. Additionally, other public economic and local government programs may be available, including job training, economic development areas, and increased grant and loan opportunities that can have a positive financial effect directly to the project as well as to the greater community.

Direct costs of remediation alternatives and activities are often compared during the cost-benefit evaluation process. The comparison and follow-up documentation of these cost-benefit analyses can provide a solid economic justification for sustainable methodologies and the value of sustainable business practices. While this element is primarily economic, it could benefit social and environmental aspects as well.

Several example BMPs associated with sustainable objectives that may be considered for a remediation project are presented in Table 4.2. To the extent feasible, as many BMPs as possible should be selected and implemented to address the sustainable objectives in a given remediation

Table 4.2. ASTM sustainable remediation BMPs

Core element	Additional core elements benefitted	BMP
Air emissions	Energy Materials and waste	Buy carbon offset credits (for example, for airline flights) when in-person meetings are required.
Air emissions	Energy Efficiencies in cleanup and cost savings Materials and waste	Implement a telemetry system to reduce frequency of site visits.
Air emissions	Energy Efficiencies in cleanup and cost savings	Implement an idle reduction plan to reduce the amount of vehicle idling at the cleanup site.
Air emissions	Efficiencies in cleanup and cost savings Materials and waste	Install one-way check valves in well casing to promote barometric pumping (passive SVE) as a polishing step once the bulk of contamination has been removed and venting to atmosphere is acceptable.
Air emissions	Energy Efficiencies in cleanup and cost savings	Minimize diesel emissions through the use of retrofitted engines, low sulfur diesel or alternative fuels, or filter or treatment devices.
Air emissions	Energy Efficiencies in cleanup and cost savings	Use biodiesel produced from waste or cellulose based products, preferring local sources when available to reduce transportation impacts

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Air emissions	Materials and waste	Use teleconferences rather than inperson meetings when feasible.
Air emissions	Energy Efficiencies in cleanup and cost savings	Use variable frequency drive motors to automatically adjust energy use to meet system demand on blowers, vacuum pumps, and so on. that accommodate changes in operating requirements as treatment progresses
Air emissions	Energy	When nearing asymptotic conditions or when continuous pumping is not needed to contain the plume and reach clean-up objectives, operate pumping equipment in pulsed mode
Air emissions	Energy Efficiencies in cleanup and cost savings Materials and waste	Replace conventional vehicles with electric, hybrid, or compressed natural gas vehicles
Air emissions	Energy Efficiencies in cleanup and cost savings Materials and waste	Use rebuilt or replaced engines to maximize emission reductions.
Community involvement	Local community vitality	Develop templates of communication strategies
Community involvement		Use a neutral party convener or facilitator for community engagement activities.

Community involvement	Local community vitality	Amend planned remedial actions where stakeholder comments or concerns have merit and where feasible. Communicate the updates to the community using forums that have been identified as the most effective for that area. Communication sources could include: local news spots or articles, social networking sites, mailing to community groups, and so on.
Community involvement	Local community vitality	Take steps to include stakeholder needs
Community involvement	Local community vitality	Communicate public participation requirements set out in differently regulatory programs to stakeholders.
Community involvement	Local community vitality	Communicate site activities to stakeholders and the community in a nontechnical fashion so that issues of public health risk are understood.
Community involvement	Local community vitality	Conduct a public involvement charrette during remediation design early in the project where possible, at times and places that, to the extent feasible, facilitate attendance or involvement by the affected public. Notify the public of potential consultation and involvement activities early enough to ensure the public has adequate time to obtain and evaluate information; consult experts, and formulate and express their opinions, options, and suggestions prior to completing specific project steps (action). Involve the public during remedy implementation and remedy operation, using methods described in this Appendix: X1.

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMPs
Community involvement	Economic impacts to the local community (for example neighborhood)	Conduct onsite citizen training sessions (for members of the local community) that directly relate to site assessment and cleanup efforts.
Community involvement	Local community vitality	Consider clean-up technologies which are favorable to each of the different stakeholders identified when appropriate or possible
Community involvement	Local community vitality	Develop a contact list by consulting with community organizations and add to the list those members of the public who request they be added. Update the list regularly and subdivide the list by category of interest or geographic area. Use the list to send announcements reports and other communication with the public.
Community involvement	Local community vitality	Empathize with stakeholders. Listen carefully to what stakeholders are saying
Community involvement	Local community vitality	At the start of the project, establish clear lines of communication with stakeholders, particularly the local community.
Community involvement	Local community vitality	Establish regular meetings and workshops to provide information to the public on the status of the project. The number of meetings will be based on stakeholder needs and will be site-specific.

Community involvement	Local community vitality	Extend public participation activities beyond regulatory requirements, especially for sites with impacts extending beyond the site boundary. Set up a hotline or web site that community members can access to aid in public participation.
Community involvement	Local community vitality	Follow through on one or more recommendations that was generated during the remediation design charrette.
Community involvement	Local community vitality	Identify a community liaison for effective stakeholder communication.
Community involvement	Local community vitality	Identify and implement opportunities to enhance community dynamics
Community involvement	Local community vitality	Identify organizations with common environmental, social, or economic concerns. Determine how best to partner with these organizations or individuals to build a relationship with the local community.
Community involvement	Local community vitality	Identify the various groups who constitute the stakeholders and the community.
Community involvement	Local community vitality	Implement strategies to develop a more collaborative relationship with stakeholders beyond existing regulatory requirements to the extent possible, for example by engaging the stakeholders and increasing the transparency of operations at the site.
Community involvement	Local community vitality	Monitor on a continuing basis, both the effectiveness of the efforts to improve public involvement, and the effectiveness of public involvement activities.

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Community involvement	Local community vitality	Obtain and review stakeholder feedback early in the project and implement to the extent possible.
Community involvement	Economic impacts to the local community (for example, neighborhood)	Plan and budget for the public involvement. Budget documents should include resources for public involvement separate from and in addition to funds required to comply with statutes and executive orders that require public involvement.
Community involvement	Local community vitality	Provide feedback to stakeholders.
Community involvement	Economic impacts to the local community (for example, neighborhood)	Provide financial assistance for public involvement, when needed, for example providing public transportation to public meetings for community members.
Community involvement	Local community vitality	Provide the public with adequate and timely information concerning forthcoming actions or decisions. Fact sheets, news releases, summaries, and similar publications in print and on the Internet may be used to provide notice of availability of materials.
Community involvement	Local community vitality	Resolve conflicts, for example, diverging opinions about site end uses or redevelopment, with stakeholders as early as possible.
Community involvement	Local community vitality	Respond to stakeholder questions and concerns in a timely fashion to ensure that their needs are addressed as quickly as possible.

Community involvement	Local community vitality	Take steps to resolve conflicts among stakeholders regarding site end uses or redevelopment as early as possible by acknowledging and recording each divergent opinion.
Economic impacts to the local community (for example, neighborhood)	Economic impacts to the local government (for example, city or county)	Acquire supplies such as cleanup products, safety supplies, work equipment, fuels and lubricants from the area of or adjacent to the cleanup site to the maximum extent practicable.
Economic impacts to the local community (for example, neighborhood)	Economic impacts to the local government (for example, city or county)	Encourage contractors to use local services while working on the site (for example motels, trailer parks, restaurants, grocery stores) from the area of or adjacent to the cleanup site to the maximum extent practicable.
Economic impacts to the local community (for example, neighborhood)	Community involvement	Gather information on each potential contractor's and supplier's social responsibility for its employees. Review wages, benefits, personnel policies and discrimination complaints during the contractor and supplier selection process where feasible.
Economic impacts to the local community (for example, neighborhood	Economic impacts to the local government (for example, city or county)	Identify a postcleanup land-use development type which spurs the neighborhood-scale economy, without displacing legacy residents.
Economic impacts to the local community (for example, neighborhood)	Local community vitality	Make provisions to accommodate temporary access to local businesses, public facilities and residences to the extent possible.

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	**Additional core elements benefitted**	**BMP**
Economic impacts to the local community (for example, neighborhood)	Community involvement	Modify cleanup approaches to address concerns about disruptions and disturbances to local residents and businesses. Solicit opinions from local residents and implement suggested mitigation measures that are appropriate.
Economic impacts to the local community (for example, neighborhood	Materials and waste	Provide on-site collection and storage area for compostable materials for use on-site or by the local community
Economic impacts to the local community (for example, neighborhood	Economic impacts to the local government (for example, city or county)	Use local staff (including subcontractors) when possible to minimize resource consumption
Economic impacts to the local government (for example, city or county)	Economic impacts to the local community (for example, neighborhood)	Employ local contractors, where possible. Hire labor including skilled and professional labor as well as manual labor from the area of or adjacent to the cleanup site to the maximum extent practicable. Labor includes subcontractors, part-time labor, security, environmental technicians, professional geologists, professional engineers, and health and safety professionals. The project could specify a minimum percentage of jobs that must be given to qualified local residents and businesses, or semiqualified residents who can be qualified with minimal training.

Economic impacts to the local government (for example, city or county)	Economic impacts to the local community (for example, neighborhood)	Encourage the provision of training (for example, Hazwoper training per 29 CFR 1910.120) for the local workforce (for example, apprenticeships for young adults between the ages of 18 to 25) so as to expand opportunities for site employment activities.
Economic impacts to the local government (for example, city or county)	Economic impacts to the local community (for example, neighborhood)	Identify and implement innovative techniques to create economically and socially sustainable opportunities. Techniques may include (1) looking for funded programs from a local, State, or federal agencies to improve postremediation land use (for example, parks, stormwater management, community gardens, or green market), (2) requesting temporary property tax waivers for neighboring property owners impacted by the remediation project so as to avoid adverse effects.
Economic impacts to the local government (for example, city or county)	Materials and waste	Incorporate project and she activities into local recycling program, requirements and regulations
Economic impacts to the local government (for example, city or county)	Economic impacts to the local community (for example, neighborhood)	Place or keep private property (at or near cleanup site) on local government tax rolls.
Economic impacts to the local government (for example, city or county)	Economic impacts to the local community (for example, neighborhood)	Purchase equipment and materials locally when available

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Economic impacts to the local government (for example, city or county)	Energy Materials and waste	Reuse, recycle or retrofit equipment where feasible. With public and environmental health and safety aspects being equal, reusing or recycling cleanup equipment, (or scheduling equipment across a group of similar small sites), reduces the cost of equipment uses the equipment more efficiently and avoids the waste of throwing away equipment. There may also be opportunities to repurpose equipment following cleanup for other needs in the community.
Economic impacts to the local government (for example, city or county)	Economic impacts to the local community (for example, neighborhood) air emissions	Use a local laboratory for environmental sample analysis to minimize impacts from transportation, improve the local economy, and generate good relations with the public.
Efficiencies in cleanup and cost savings		Complete all required documentation at the time activities are performed
Efficiencies in cleanup and cost savings	Energy	Determine appropriate season to conduct work to reduce weather delays and additional heating or cooling demands
Efficiencies in cleanup and cost savings	Materials and waste	Incorporate BMPs into contracting and procurement

Efficiencies in cleanup and cost savings	Economic impacts to the local community (for example, neighborhood) Economic impacts to the local government (for example, city or county)	Perform a cost analysis of the cleanup with and without sustainable objectives for the entire she assessment and cleanup project. The user may find that conducting a cost analysis for the entire cleanup with and without sustainable objectives will help to identify opportunities for additional improvements in cleanup efficiency as well as opportunities to improve the environmental or social aspects of the cleanup. This analysis may have the added benefit to document the value of sustainable business practices that will benefit the local community.
Efficiencies in cleanup and cost savings	Local community vitality	Select a site assessment and cleanup alternative that is lower in cost to the user that also yields positive benefits to the community, provided compliance with all environmental and worker or public health regulations is assured.
Efficiencies in cleanup and cost savings	Energy Materials and waste	Use direct sensing noninvasive technology such as a membrane interface probe, X-ray fluorescence, laser-induced fluorescence (LIF) sensor, cone penetrometer testing (CPT), electrical resistivity tomography, and seismic refraction or reflection
Efficiencies in cleanup and cost savings	Energy	Use equipment to increase automation such as electronic pressure transducers, thermo-couples and water quality monitoring devices coupled with an automatic data logger.
Efficiencies in cleanup and cost savings	Materials and waste	Use field test kits for screening analysis of soil and groundwater contaminants such as petroleum, polychlorinated biphenyls, pesticides, explosives, and inorganics

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Efficiencies in cleanup and cost savings	Materials and waste	Use on-site mobile lab or other field analysis (for example, portable gas chromatography or mass spectrometry for fuel-related compounds and VOCs)
Efficiencies in cleanup and cost savings	Energy Water impacts Land and ecosystems	Use seasonal removal (for example, cold or dry) or ground-freezing technologies, if environmentally beneficial, to minimize dewatering prior to excavation
Energy	Efficiencies in cleanup and cost savings Materials and waste	Build energy efficient heating and cooling into new buildings by using natural conditions such as prevailing wind directions for cooling and heating, passive solar building design, and existing shade
Energy	Efficiencies in cleanup and cost savings Materials and waste	Build energy efficiency lighting into new buildings by using natural conditions such as passive lighting and by using designed systems such as energy star lighting.
Energy	Efficiencies in cleanup and cost savings	Capture on-site waste heat (for example, treatment plant effluent, ground-source heat pumps, mobile waste-to-heat generators, or furnaces and air conditioners operating with recycled oil) to power cleanup activities
Energy	Efficiencies in cleanup and cost savings Materials and waste	Design energy efficient HVAC systems (for example, programmable heating and cooling systems)

Energy		Employ auxiliary power units to power cab heating and air conditioning when a machine is not operating (such as smartway generator or plug in outlet)
Energy		Install a modular renewable energy system that can be used to meet energy demands of multiple activities over the lifespan of the project (for example, powering field equipment, construction or operational activities, and supplying energy demands of buildings)
Energy		Install amp meters to evaluate consumption rates on a real-time basis to evaluate options for off-peak energy usage
Energy		Insulate all applicable pipes and equipment to improve energy efficiency
Energy	Efficiencies in cleanup and cost savings	Operate all on-site equipment during off-peak hours of electrical demand, without compromising cleanup progress
Energy		Prevent damage to equipment through use of surge protection devices, and program the equipment to restart in phases to avoid additional power surges that trip circuit breakers
Energy	Efficiencies in cleanup and cost savings Materials and waste	Properly insulate buildings
Energy	Air emissions	Purchase renewable energy via local utility and green energy programs or renewable energy credits or certificates (RECs or Green Taps) to power cleanup activities

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Energy	Efficiencies in cleanup and cost savings Materials and waste	Reuse or recycle recovered product (such as resale of captured petroleum products, precipitated metals) and materials (for example, cardboard, plastics, asphalt, concrete)
Energy	Air emissions	Use a gravity flow to introduce amendments or chemical oxidants to the subsurface when high-pressure injection is unnecessary
Energy	Efficiencies in cleanup and cost savings Materials and waste	Use biodegradable hydraulic fluids on hydraulic equipment such as drill rigs
Energy		Use compact fluorescent lighting (CFL) or LED lighting in all on-site equipment and properly recycle CFLs or LEDs.
Energy		Use Energy Star appliances
Energy		Use gravity flow where feasible to reduce the number of pumps for water transfer after subsurface extraction
Energy	Efficiencies in cleanup and cost savings Materials and waste	Use heat pumps or solar heating in place of electrical resistive heating when preheated extracted groundwater is required prior to treatment.
Energy	Efficiencies in cleanup and cost savings Materials and waste	Use materials that are made from recycled materials (for example, steel, concrete, plastics and asphalt; tarps made with recycled or biobased contents instead of virgin petroleum-based contents)

Energy		Use on-site generated renewable energy (for example, solar photovoltaic, wind turbines, landfill gas, geothermal, and biomass combustion) to power cleanup activities
Energy	Economic impacts to the local community (for example, neighborhood) Efficiencies in cleanup and cost savings Materials and waste	Use on-site or local materials when installing cap
Energy		Use programmable thermostats to minimize energy use
Energy		Use pulsed rather than continuous injections when delivering or extracting air to increase energy efficiency when nearing asymptotic conditions
Energy		Use solar power pack system for low-power system demands (for example, security lighting, system telemetry)
Enhancement of individual human environments	Local community vitality	Adopt and implement assessment and cleanup steps and sequences that design-out opportunities for accidents, emergencies, and spill events.
Enhancement of individual human environments	Local community vitality	Cleanup contractors document holding regular (for example, daily morning, prework day “tailgate”) health and safety meetings with cleanup site workers, identifying possible hazards for the day and measures in place to mitigate hazard risks.

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	**Additional core elements benefitted**	**BMP**
Enhancement of individual human environments	Local community vitality	Consider weather effects on workers health and safety above and beyond the minimum required by law or liability. Evaluate potential exposure to hot, cold, or humid conditions and determine the necessary rest period. Ensure workers wear protective clothing based on hot, cold, or humid conditions weather.
Enhancement of individual human environments	Materials and waste	Contract laboratory that uses sustainable practices and chemicals
Enhancement of individual human environments	Community involvement	Create fact sheets describing site conditions, technologies employed and so on and make them available to the public for example through a website or at a library. Include information on how the technology works, its advantages and disadvantages, and why the technology was selected. The fact sheets should address site-specific stakeholder needs and should identity the sustainable aspects of the project.
Enhancement of individual human environments	Economic impacts to the local community (for example, neighborhood)	Ensure that the health and safety plans of all organizations working at the site are available for review.
Enhancement of individual human environments	Land and ecosystems	Establish sustainable requirements (for example, BMPs) as evaluation criteria in the selection of contractors and include language in RFPs. RFQs, subcontracts, contracts, and so on.

Enhancement of individual human environments	Local community vitality	Identify members of the local community who may be more vulnerable to environmental hazards. Ensure the fair treatment and meaningful involvement of all people affected by the project regardless of gender, age, race, color, national origin, sexual orientation physical ability or income.
Enhancement of individual human environments	Community involvement	Implement a local education program about site impacts and remediation impacts.
Enhancement of individual human environments	Economic impacts to the local community (for example, neighborhood) Economic impacts to the local government (for example, city or county)	Include specific focus on sustainable aspects at technical scoping and kick-off meetings and periodic meetings with all parties including clients, stakeholders, regulatory agencies, and consultants; Update project team if goals and responsibilities change.
Enhancement of individual human environments	Local community vitality	Minimize site noise levels. For example, insulate pumps, blowers and other active equipment, maximize vehicle mufflers, and limit vehicle movement to business hours.
Enhancement of individual human environments	Local community vitality	Monitor potential adverse impacts at the site and communicate or post the results on a regular basis.
Enhancement of individual human environments	Enhancement of individual human environments	Reduce or mitigate dust-generating activities. Use of heavy equipment and vehicles on sites can generate dust that is a nuisance to the community and a health hazard to people with respiratory illness. Take actions to either minimize the use of equipment or to mitigate through techniques such as water application to reduce dust.

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	**Additional core elements benefitted**	**BMP**
Enhancement of individual human environments	Enhancement of individual human environments	Reduce or optimize light-generating activities during night time operations to minimize impact to the community.
Enhancement of individual human environments	Air emissions Materials and waste	Select facilities with sustainable policies for worker accommodations and periodic meetings
Enhancement of individual human environments	Local community vitality	Solicit and evaluate potential contractor's proposed health and safety plans, practices, and safety record above and beyond the minimum required by law or liability during the contractor selection process.
Enhancement of individual human environments	Land and ecosystems	Soundproof all aboveground equipment housing to prevent noise disturbance to surrounding environment
Enhancement of individual human environments	Economic impacts to the local community (for example, neighborhood)	Take actions to either reduce truck traffic or mitigate the impacts of traffic that could pose a risk to community members due to accidents.
Enhancement of individual human environments	Energy Materials and waste Air emissions Land and ecosystems	Use centrifugal blowers, rather than positive displacement blowers, and intake air line mufflers to decrease noise levels

Enhancement of individual human environments	Materials and waste	Use methods to prevent contaminant spreading during various project stages above and beyond the minimum required by law or liability. For example, cover the waste and any contaminated areas where active work is not performed instead of water spraying or other energy intensive methods for dust suppression.
Enhancement of individual human environments		Purchase products from vendors that pay employees a living wage.
Enhancement of individual human environments		Use contractors and vendors that have a strong environmental track record.
Land and ecosystems	Materials and waste	Cover filled excavations with biodegradable fabric to control erosion and serve as a substrate for ecosystems
Land and ecosystems	Materials and waste	Enhance existing natural resources and promote carbon sequestration by incorporating wetlands, bioswales and other types of vegetation into overall remedial approach.
Land and ecosystems		Maximize vegetative cover across the site during restoration
Land and ecosystems	Efficiencies in cleanup and cost savings Materials and waste	Minimize clearing of trees throughout investigation and cleanup
Land and ecosystems	Materials and waste	Restore and maintain surface water banks in ways that mirror natural conditions

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	**Additional core elements benefitted**	**BMP**
Land and ecosystems	Materials and waste	Salvage uncontaminated and pest- or disease-free organic debris, including trees downed during site clearing, for use as fill, mulch, compost, or habitat creation
Land and ecosystems	Materials and waste	Use a leachate collection system for a landfarm (along with a leachate treatment system) to fully preserve the quality of downgradient, water bodies, soil and groundwater
Land and ecosystems	Materials and waste	Use excavated areas to serve as retention basins in final stormwater control plans
Land and ecosystems	Materials and waste	Use gravel roads, porous pavement and separated pervious surfaces to maximize infiltration
Land and ecosystems	Materials and waste	Use nonchemical solarizing techniques to minimize need for pesticide use during restoration
Local community vitality	Enhancement of individual human environments	Ensure site is secure at all times
Local community vitality	Materials and waste	Ensure that the site is kept neat, clean and orderly during the clean-up process. Implement programs to avoid site degradation from on-site activities. Assign staff to police the area and remove trash on a regular basis. Provide recycling, solid waste disposal and sanitary facilities for site workers.

Local community vitality	Enhancement of individual human environments	Identify potential environmental services that could be provided by unused space, consider using native vegetation and landscaping to incorporate these services (for example, wetlands).
Local community vitality	Air emissions	Minimize adverse effects to existing local traffic flow and patterns. Plan out truck traffic patterns that minimize impacts to the community and infrastructure and to drive on roads during times of lower traffic to reduce public risks. If local traffic flows and patterns need to be temporarily disrupted, solicit and coordinate temporary traffic plans with appropriate governmental agency.
Local community vitality	Enhancement of individual human environments	Minimize working at night during weekends, and holidays if the task has the potential to generate noise or other nuisances for nearby residents, businesses, or community functions (for example, sporting events).
Local community vitality	Enhancement of individual human environments	Minimize the intensity, pitch, frequency, and duration of all noises or vibrations from the cleanup site at all times
Local community vitality	Enhancement of individual human environments	Provide public training on sustainability.
Local community vitality	Materials and waste	Provide solid waste collection and disposal service during social hours.
Local community vitality	Enhancement of individual human environments	Restore site surroundings so that they are visually attractive

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Local community vitality	Enhancement of individual human environments	Select a site assessment and cleanup alternative that can be completed as soon as possible, provided compliance with all environmental and worker or public health regulations is assured; the exception to this is the situation whereby an ongoing subsurface remediation system is operating (within its terminal mode without the need for frequent adjustments to air or chemical flow rates [for example, monitored natural attenuation cleanup phase]) and site is available for its designated postcleanup land use.
Local community vitality	Enhancement of individual human environments	Use sustainable landscaping to restore vegetation at the minimum to its preproject level. For each tree that is cut, plant new ones and use local or indigenous species.
Materials and waste	Water impacts	Consider discharging wastewater to a POTW or other regional water treatment plant rather than building and operating an on-site treatment plant, when feasible and environmentally beneficial based on additional analysis
Materials and waste	Water impacts	Construct engineering controls such as earth dikes and swales to prevent upgradient surface flow into excavated areas
Materials and waste	Water impacts	Employ closed-loop graywater washing system for decontamination of trucks

Materials and waste		Implement a flexible network of piping which allows for future modular increases or decreases in the extraction or injection rates and treatment modifications
Materials and waste	Efficiencies in cleanup and cost savings	Install energy recovery ventilators to allow incoming fresh air while capturing energy from outgoing, conditioned air
Materials and waste	Water impacts	Install silt fences and basins to capture sediment runoff along sloped areas
Materials and waste		Integrate schedules to allow for resource sharing and fewer days of field mobilization
Materials and waste	Energy	Maintain vehicles on a regular basis such as tune-ups and proper tire inflation. Use green vehicle maintenance products such as biodegradable lubricants.
Materials and waste		Maximize the reuse of existing wells for injections or extractions
Materials and waste	Water impacts	Minimize off-site disposal of solid waste by improving solids dewatering with a filter press or other technologies
Materials and waste	Efficiencies in cleanup and cost savings	Minimize the size of the housing for above-ground treatment system and equipment
Materials and waste		Minimize use of pesticides through the use of green alternatives and an integrated pesticide management plan.
Materials and waste		Prepare, store, and distribute documents electronically
Materials and waste	Efficiencies in cleanup	Provide sanitary facilities for site workers.

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Materials and waste		Purchase liquids in concentrated form to reduce shipping volumes and frequencies
Materials and waste		Purchase materials in bulk quantities and packed in reusable or recyclable containers and drums to reduce packaging waste
Materials and waste		Reclaim and stockpile uncontaminated soil for use as fill or other purposes
Materials and waste	Water impacts	Recycle condenser water as supplemental cooling water where contaminant concentrations permit
Materials and waste	Efficiencies in cleanup and cost savings	Retain equipment that has potential for reuse
Materials and waste	Efficiencies in cleanup and cost savings	Reuse existing structures for treatment system, storage, sample management, and so on
Materials and waste	Efficiencies in cleanup and cost savings	Segregate drilling waste based on location and composition to reduce the volume of drilling waste disposed off-site; collect needed analytical data to make on-site reuse decisions.
Materials and waste	Efficiencies in cleanup and cost savings	Segregate hazardous waste and nonhazardous waste

Materials and waste	Water impacts	Treat condensate in onsite systems where contaminant types and concentrations permit
Materials and waste	Water impacts	Treat potentially contaminated purge water with an on-site treatment technique prior to reinjecting into an on-site well, or discharge to a storm drain or waterway, as permissible
Materials and waste		Use biodegradable cleaning products
Materials and waste		Use by-products, waste or less refined materials from local sources in place of refined chemicals or materials (for example, cheese whey, molasses, compost, or off-spec food products for inducing anaerobic conditions; limestone in place of concentrated sodium hydroxide)
Materials and waste	Efficiencies in cleanup cost savings	Use filters (for example, bag or cartridge filters) that can be backwashed to avoid frequent disposal of filters
Materials and waste	Water impacts	Use low flow sampling methods
Materials and waste		Use paper with recycled content and use double-sided printing option when document must be printed
Materials and waste		Use products, packing material, and equipment (for example, laboratory containers) that can be reused or recycled
Materials and waste		Use rechargeable batteries for handled data loggers and other field instruments

(*Continued*)

Table 4.2. ASTM sustainable remediation BMPs (*Continued*)

Core element	Additional core elements benefitted	BMP
Materials and waste		Use timers or feedback loops and process controls for dosing for injection of chemicals
Materials and waste	Water impacts	Use uncontaminated wastewater or treated water for tasks such as wash water, irrigation, dust control, constructed wetlands or other uses
Materials and waste	Efficiencies in cleanup and cost savings	Use wood based materials and products that are certified in accordance with the Forest Stewardship Council (FSC) Principles and Criteria for wood building components
Materials and waste	Energy Efficiencies in cleanup and cost savings	Consider preheating vapors to reduce relative humidity prior to treatment with vapor-phase GAC to improve adsorption efficiency when additional analysis supports approach
Materials and waste	Energy Efficiencies in cleanup and cost savings	Salvage uncontaminated objects with potential recycle, resale, donation, or onsite infrastructure value such as steel, concrete, granite, and storage containers
Materials and waste	Efficiencies in cleanup and cost savings	Steam-clean or use phosphate-free detergents instead of organic solvents or acids to decontaminate sampling equipment
Materials and waste	Energy Efficiencies in cleanup and cost savings	Use regenerated GAC for use in carbon beds

Water impacts	Efficiencies in cleanup and cost savings	Divert upgradient, uncontaminated groundwater around a contaminant plume to reduce the amount of water extracted and/or treated; when feasible based on additional analysis
Water impacts		Install a landfarm rain shield (such as a plastic tunnel) with rain barrels or a cistern to capture precipitation for potential onsite use
Water impacts	Efficiencies in cleanup and cost savings	Reclaim clean or treated water from other site activities for use in injection slurries or as injection chase water
Water impacts		Reinject treated groundwater to the subsurface to recharge an aquifer
Water impacts	Land and ecosystem	Use captured rainwater for tasks such as wash water, irrigation, dust control, constructed wetlands or other uses
Water impacts		Use dewatering processes that maximize water reuse
Water impacts	Efficiencies in cleanup and cost savings	Use treated slurry water for other cleanup activities or nonremedial applications such as irrigation or wetlands enhancement

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project. The BMPs should be selected across the environmental, economic, and social dimensions to provide the greatest net sustainable benefit associated with the proposed remediation project. Additionally, the impacts of the implemented BMPs may be quantified for a remediation alternative considered for the specific site under consideration. Some BMPs may not include quantifiable attributes and therefore quantification may not be possible. Nevertheless, many of the BMPs may be easily and accurately quantified to determine contribution to benefits associated with project sustainability.

4.6 SELECTED INTERNATIONAL FRAMEWORKS

The United Kingdom's Sustainable Remediation Forum (SuRF-UK) published a framework for assessing the sustainability of soil and groundwater remediation (SuRF-UK 2009). This framework provided a connection between the principles of sustainable development and criteria (environmental, social, and economic) for selecting optimum land use design with sustainable remediation strategies and treatments. In developing their framework, the SuRF-UK engaged with a wide range of stakeholders across a broad range of organizations working in contaminated land and brownfield management. As with the other frameworks developed and presented in this chapter, the SuRF-UK framework emphasizes the importance of considering sustainability issues throughout all key stages of a remediation project and identifies opportunities for considering sustainability at a number of milestones or decision points when considering the redevelopment potential of a site or related risk management activities.

The Network for Industrially Contaminated Land in Europe (NICOLE) is a European forum that focuses on contaminated land management and promotes cooperation between industry, academia, and service providers on the development and application of sustainable technologies. NICOLE published *Sustainable Remediation Road Map* (NICOLE 2010), which is intended to provide users, including owners and operators of contaminated land and related stakeholders, with a single, structured process to facilitate cooperation and the implementation of best practices in sustainable remediation across a wide range of regulatory and policy frameworks.

4.7 SUMMARY

There is no universally accepted framework for evaluating the sustainability of remediation projects. Fortunately, several frameworks have been developed by a range of organizations that can be used to effectively assess sustainability-related parameters of remediation projects. The frameworks presented in this chapter are varied in their depth and breadth of analysis of these parameters. Fortunately, this allows for the opportunity to select a framework of appropriate applicability and complexity based on the characteristics of the remediation project under consideration. In some cases, only environmental, or green, related aspects are desired for characterization. In these instances, the U.S. EPA framework and its core elements of green remediation are appropriate for consideration. In other cases, more direct measurement of social and economic parameters are desired; in these instances, one or more of the other frameworks presented in this chapter may be selected and utilized. In virtually all instances, these frameworks generally emphasize or aim toward the U.S. EPA-based core elements.

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

The economic and social aspects can be complex and may be best addressed through BMPs, but due to their equal importance in considering sustainability aspects of remediation projects, there is a rapidly increasing emphasis on accurate incorporation, assessment, and documentation of these aspects. Continued efforts are warranted for their quantitative evaluation.

CHAPTER 5

SUSTAINABLE REMEDIATION INDICATORS, METRICS, AND TOOLS

5.1 INTRODUCTION

In the previous chapter, several frameworks were presented that may be used to evaluate the sustainability of a remediation project across one or more of the dimensions of sustainability, including those associated with environmental, economic, and social aspects. When performing a sustainability analysis of remediation project alternatives or best management practices (BMPs) that may be considered for inclusion into a project, it is important to identify key indicators that may be used to assess the project. These indicators, in turn, may be expressed with a numerical value, or metric. When expressed on a relative or absolute scale, these metrics may be used to determine the degree of success and progress that a particular project or alternative may realize with respect to sustainability dimensions. Numerous indicators and metrics have been developed to measure the sustainability of remediation projects. Further, several qualitative and quantitative tools have been developed to calculate and amass these metrics toward providing an objective evaluation.

As with the case of the sustainability frameworks that were presented in the previous chapter, there is no consensus regarding key indicators and metrics, nor have there been any legitimate or accepted efforts toward standardization of the process. As a result, a wide range of indicators and metrics are often selected and incorporated into analyzes, and some confusion regarding terminology persists. This adds an additional challenge with respect to the uniform evaluation of a wide range of projects. Further, while environmental sustainability indicators, metrics, and tools are still emerging and are under development, they are considered relatively advanced as compared to metrics and related evaluations of economic sustainability and social sustainability, which still remain in their infancy.

This chapter presents sustainability indicators and metrics to quantify them. Additionally, a variety of simple and advanced qualitative and quantitative tools that have been developed to assess sustainability are presented and discussed.

5.2 SUSTAINABILITY INDICATORS

Sustainability indicators are measurable aspects of environmental, economic, or social dimensions associated with potential remediation alternatives for a project. Because they are measurable, these indicators can be estimated beforehand or monitored on a real-time or periodic basis to determine how a particular project or project alternative and its sustainability characteristics may positively (or negatively) contribute to human health or environmental health. As with many goals and objectives related to project management in a range of fields or industries, a sustainability indicator should have the following attributes defined by the SMART attributes:

- Specific: the indicator should target a specific area for consideration and analysis. It identifies the *what*, *when*, or *how*. As an example, an indicator for a project alternative or alternatives may be the minimization of emissions of particulate matter less than 10 microns in diameter (PM_{10}). PM_{10} emissions can exacerbate those with respiratory ailments, such as asthma or chronic lung disease, and can also lead to other long-term adverse health effects. A specific indicator may be through the use of emissions controls on heavy equipment at a project site.
- Measurable: the indicator should be capable of being counted, compiled, analyzed, or tested so that a data set can be collected and assessed to determine the degree of success. In our example, filters or other measurement devices can be deployed at or near a project to measure PM_{10} emissions. Baseline or ambient conditions may also be established to determine the degree to which the project may contribute to the measured indicator.

- Actionable or achievable: the indicator should have a clear performance target that is easily understandable and may be realistically achieved with methods to be applied to the project. For instance, if heavy diesel-powered equipment is to be used at a project, in may be unrealistic to expect zero PM_{10} emissions; however, another performance standard, such as a 50 percent reduction compared to previous projects where emissions controls were not required may be appropriate and achievable.
- Relevant: the indicator should be selected such that it has a meaningful contribution to the overall goal or strategy associated with the project. Many indicators can be selected for a given project; however, they should be critically assessed for their overall meaningful contribution to the environmental, economic, or social dimensions of sustainability for a project. In the PM_{10} example, it is relatively easy to demonstrate that reduced PM_{10} emissions have a direct benefit to project environmental conditions as well as meaningful contributions to economic and social dimensions by protecting human health, quality of life, and associated economic benefits.
- Timely: the indicator should be achieved within an appropriate time frame or be subjected to the time constraints of the project. For this example, the 50 percent PM_{10} reduction may be assigned to the life of the project or over a specific subset of time, such as a period when equipment operations will be the greatest and PM_{10} reductions are most necessary.

The key indicators as discussed earlier may be objective or subjective. As an example, the United Nations developed measurable objective indicators for sustainable development; these indicators are shown in Table 5.1.

In considering remediation projects with respect to sustainability, key indicators are essential to the evaluation of a project, whether they are considered objective or subjective indicators. All aspects of a remediation project may be considered on an individual, discrete basis, whether this constitutes the site characterization phase, the physical remediation phase, or the postremediation monitoring phase. Additionally, any combination of these phases, of the entire remediation process, may be considered when assessing sustainability.

Further, when considering the sustainable aspects of a remediation project, it is essential to consider indicators representative of all three of the dimensions that constitute the triple bottom line: environmental,

Table 5.1. UN sustainability indicators

Theme	Subtheme	Core indicator	Other indicator
Poverty	Income poverty	Proportion of population living below national poverty line	Proportion of population below $1 a day
	Income inequality	Ratio of share in national income of highest to lowest quintile	
	Sanitation	Proportion of population using an improved sanitation facility	
	Drinking water	Proportion of population using an improved water source	
	Access to energy	Share of households without electricity or other modern energy services	Percentage of population using solid fuels for cooking
	Living conditions	Proportion of urban population living in slums	
Governance	Corruption	Percentage of population having paid bribes	
	Crime	Number of international homicides per 100,000 population	
Health	Mortality	Under-five mortality rate	
		Life expectancy at birth	Healthy life expectancy at birth
	Health care delivery	Percent of population with access to primary health care facilities	Contraceptive prevalence rate

		Immunization against infectious childhood diseases	
	Nutritional status	Nutritional status of children	
	Health status and risks	Morbidity of major diseases such as HIV/AIDS, malaria, tuberculosis	Prevalence of tobacco use
			Suicide rate
Education	Education level	Gross intake ratio to last grade of primary education	Life long learning
		Net enrolment rate in primary education	
		Adult secondary (tertiary) schooling attainment level	
	Literacy	Adult literacy rate	
Demographics	Population	Population growth rate	Total fertility rate
		Dependency ratio	
	Tourism		Radio of local residents to tourists in major tourists region and destinations
Natural hazards	Vulnerability to natural hazards	Percentage of population living in hazard prone areas	
	Disaster preparedness and response		Human and economic loss due to natural disasters

(*Continued*)

Table 5.1. UN sustainability indicators (*Continued*)

Theme	Subtheme	Core indicator	Other indicator
Atmosphere	Climate change	Carbon dioxide emissions	Emissions of greenhouse gases (GHGs)
	Ozone layer depletion	Consumption of ozone depleting substances	
	Air quality	Ambient concentration of air pollutants in urban areas	
Land	Land use and status		Land use change
			Land degradation
	Desertification		Land affected by desertification
	Agriculture	Arable and permanent cropland area	Fertilizer use efficiency
			Use of agricultural pesticides
			Area under organic farming
	Forests	Proportion of land area covered by forests	Percent of forest trees damaged by defoliation
			Area of forest under sustainable forest management

Oceans, seas, and coasts	Coastal zone	Percentage of total population living in coastal areas	Bathing water quality
	Fisheries	Proportion of fish stocks within safe biological limits	
	Marine environment	Proportion of marine area protected	Marine trophic index
			Area of coral reef ecosystems and percentage live cover
Freshwater	Water quantity	Proportion of total water resources used	
		Water use intensity by economic activity	
	Water quality	Presence of faecal Coliforms in freshwater	Biochemical oxygen demand in water bodies
			Wastewater treatment
Biodiversity	Ecosystem	Proportion of terrestrial area protected, total and by ecological region	Management effectiveness of protected areas
			Area of selected key ecosystems
			Fragmentation of habitats
	Species	Change in threat status of species	Abundance of selected key species
			Abundance of invasive alien species

(*Continued*)

Table 5.1. UN sustainability indicators (*Continued*)

Theme	Subtheme	Core indicator	Other indicator
Economic development	Macroeconomic performance	Gross domestic product (GDP) per capita	Gross saving
		Investment share in GDP	Adjusted net savings as percentage of gross national income (GNI)
			Inflation rate
	Sustainable public finance	Debt to GNI ratio	
	Employment	Employment-population ratio	Vulnerable employment
		Labor productivity and unit labor costs	
		Share of women in wage employment in the nonagricultural sector	
	Information and communication technologies	Internet users per 100 population	Fixed telephone lines per 100 population
			Mobile cellular telephone subscribers per 100 population
	Research and development		Gross domestic expenditure on R&D as a percent of GDP
	Tourism	Tourism contribution to GDP	

Global economic partnership	Trade	Current account deficit as percentage of GDP	Share of imports from developing countries and from LDCs
			Average tariff barriers imposed on exports from developing countries and LDCs
	External financing	Net official development assistance (ODA) given or received as a percentage of GNI	Foreign direct investment (FDI) net inflows and net outflows as percentage of GDP
			Remittances as percentage of GNI
Consumption and production patterns	Material consumption	Material intensity of the economy	Domestic material consumption
	Energy use	Annual energy consumption, total and by main user category	Share of renewable energy sources in total energy use
		Intensity of energy use, total and by economic activity	
	Waste generation and management	Generation of hazardous waste	Generation of waste
		Waste treatment and disposal	Management of radioactive waste
	Transportation	Modal split of passenger transportation	Model split of freight transport
			Energy intensity of transport

economic, and social dimensions. Environmental indicators may include the following:

- GHG and other air emissions
- Contributions to climate change
- Use of fresh water resources
- Impacts to soil
- Utilization of raw natural resources
- Impacts on surface water or groundwater
- Use of recycled or repurposed materials
- Overall waste generation
- Diversion of waste materials from or to landfill facilities

Economic sustainability indicators that may be considered for the remediation project include the following:

- Direct and indirect job creation within the community
- Direct and indirect investment within the community
- Facilitation of government grants for the project and community as a whole
- Long-term tax and revenue generation within the enhanced community
- Degree of highest and best use (HBU) achieved by the remediated property
- Potential to *upzone* the property and nearby properties due to remediation activity

When compared to environmental and economic dimensions, social sustainability indicators have not been incorporated as extensively, nor have they been as developed or refined. In general, social sustainability is focused on the impacts of remediation activity on society as a whole, including dimensions related to quality-of-life, diversity, cultural awareness, and social cohesion and harmony. Some key indicators of social sustainability include the following:

- Enhancement of community aesthetics
- Enhancement of quality-of-life features (e.g., improved transportation opportunities or recreational facilities)
- Public participation in decision making
- Educational and job training opportunities
- Interaction between community groups

- Emotional ownership of the community in a remediation project
- Improved physical and mental health and well-being of members of the community
- Enhanced social opportunities for members of the community
- Strengthening or enhancement of existing community institutions (e.g., recreational organizations, charitable foundations, and houses of worship)

5.3 SUSTAINABILITY METRICS

The indicators presented earlier provide key variables that may be assessed when evaluating the degree of sustainability for a particular remediation project or alternative. The indicators as presented earlier may not be easily measurable. However, numerical values or characteristics may be integrated with the indicators so that they may be objectively and accurately assessed. As a result, metrics may be connected to the indicators. Sustainability metrics are numerical values that may be used to assess specific indicators related to sustainability, and they are vitally important to objective analysis with respect to remediation project sustainability. These metrics are relatively easy to incorporate into a range of sustainability measurement tools, which are discussed in greater detail in subsequent sections of this chapter.

The metrics that may be used to assess the sustainability of environmental remediation are, in many cases, fairly straightforward and even traditional forms of measurement that are used for other purposes. As a result, their ability to be accurately measured in many cases is well established. This is especially the case for economic and environmental sustainability dimensions. As mentioned, social sustainability indicators and metrics have not been as extensively defined or developed. Further, several of the social metrics can be evaluated only qualitatively, which can make the determination of social impacts difficult. However, new tools (including the Social Sustainability Evaluation Matrix [SSEM]) are being developed with respect to the measurement of the social sustainability indicators related to remediation projects, and as a result, metrics are increasingly being applied to their analysis with increasing accuracy.

Before some common metrics are presented, it is important to note that there is no standard established regarding an appropriate set of parameters to be used for the sustainability evaluation of remediation projects, nor is there consensus on what constitutes green remediation. Additionally, there is a wide range of opinion regarding the degree to which individual metrics contribute to or affect sustainability. This is further reflected in the relatively wide range of scope inherent in several sustainability assessment tools that are presented in later sections of this chapter. Further, there is no commonly accepted set of metrics used by remediation practitioners to evaluate whether site cleanup activities are green and sustainable.

Traditional metrics associated with site remediation include the volume of remediated soil or groundwater (cubic feet and gallons or m^3 and liters), removed contaminant mass (lbs. or kg), mass of treated soil (tons or kg), or remediated area (square feet or m^2). Commonly, these metrics may also be computed based per unit time or per monetary unit basis to determine the relative time efficiency or cost efficiency of the remediation alternative.

Similar physical metrics may be used to assess the physical inputs and outputs of a remediation project alternative, including those focused or tailored for positive or negative contributions with respect to sustainability.

- Energy consumption (kWh or BTU)
- Renewable energy consumption (kWh or BTU or as a percentage of total energy consumption)
- Fresh water or recycled or reclaimed water consumption (gallons or liters)
- Air emissions (tons or kg)
- GHG emissions (tons or kg)
- Carbon emission offset (tons or kg or a percentage of GHG emissions)
- Solid waste generation (tons or kg)
- Use of recycled solid materials (tons or kg)

Several of these may be combined on a per unit basis, including energy (nonrenewable or renewable), water (fresh or reclaimed), or air emissions per treated unit mass and volume of soil or water. Of course, these may further be coupled with time or monetary unit to determine these metrics on a unit time or unit cost basis. Further, other actions may be quantitatively assessed, include credits and offsets of ecological restoration, increased real estate value on a unit basis following remediation, and preservation or restoration of natural resources or significant cultural resources or historically significant built environment.

Because the potential list of sustainability metrics for environmental remediation projects is enormous, and because there is a lack of a consensus or standard regarding key indicators and related metrics, there has been a growing dialogue between a number of sustainability-focused organizations and regulatory agencies regarding potential efforts for standardization. These organizations, including Sustainable Remediation Forum (SURF), The United Kingdom's Sustainable Remediation Forum (SuRF-UK), Association of State and Territorial Solid Waste Management Officials (ASTSWMO), and Naval Facilities Engineering Command (NAVFAC), have issued white papers and other documents to further these efforts.

For instance, SuRF-UK evaluated the application of currently available sustainability indicators to remediation in their document *A Review of Published Sustainability Indicator Sets*. It evaluated potential metrics for six indicator categories across the respective environmental, economic, and social sustainability dimensions. NAVFAC issued a fact sheet in 2009 that listed eight metrics that are applicable for use in remediation projects at contaminated sites under the jurisdiction of the U.S. Navy. These metrics include the following: energy consumption, GHG emissions, criteria pollutant emissions, water impacts, ecological impacts, resources consumption, worker safety, and community impacts. Battelle's SiteWise™ tool incorporates five metrics for the evaluation of sustainable remediation projects, including the following: consumption, GHG emissions, criteria pollutant emissions, water impacts, and worker safety. The Sustainable Remediation Tool (SRT™), developed by the Air Force Center for Engineering and the Environment (AFCEE), incorporates five metrics, including GHG emissions, energy consumed, technology cost, safety and accident risk, and natural resources services.

5.4 SUSTAINABILITY ASSESSMENT TOOLS

Once key indicators and related metrics have been devised for sustainability analyses, they may be formally evaluated using a sustainability assessment tool. A wide range of tools has been developed; each associated with a certain level of complexity and rigor associated with the analysis. The respective assessment tools may provide a relatively simple qualitative analysis of BMPs, a semiquantitative analysis, or a more complex quantitative analysis of multiple sustainability metrics. As mentioned in the previous chapter, BMPs are relatively simple to identify and implement, and qualitative analyses provide a straightforward evaluation of the benefits and drawbacks among alternatives under consideration for use. Semiquantitative and quantitative tools provide more detailed, complex evaluations of sustainability impacts. In some cases, assessment tools are in the public domain and are easily available and implemented, while other tools may be for sale and proprietarily follow a traditional software licensing platform and may be quite expensive. In some instances, not-for-profit or for-profit organizations, whether public or private, have developed assessment tools for their *in-house* use only. These tools can range from simple decision trees or spreadsheets to full life-cycle assessments (LCAs). Several qualitative, semiquantitative, and quantitative tools are summarized in the following sections.

5.4.1 QUALITATIVE ASSESSMENT TOOLS

The purpose of qualitative assessment tools is to screen remediation technology and BMP alternatives based on anticipated impacts across the environmental, economic, and societal dimensions of sustainability. These commonly consist of guidance documents or advisory manuals that outline an appropriate selection process, including relevant criteria. Two examples of qualitative tools have been developed by public regulatory agencies, including the Illinois Environmental Protection Agency (Illinois EPA) Greener Cleanup Matrix and the Minnesota Pollution Control Agency (MPCA) Toolkit for Greener Practices.

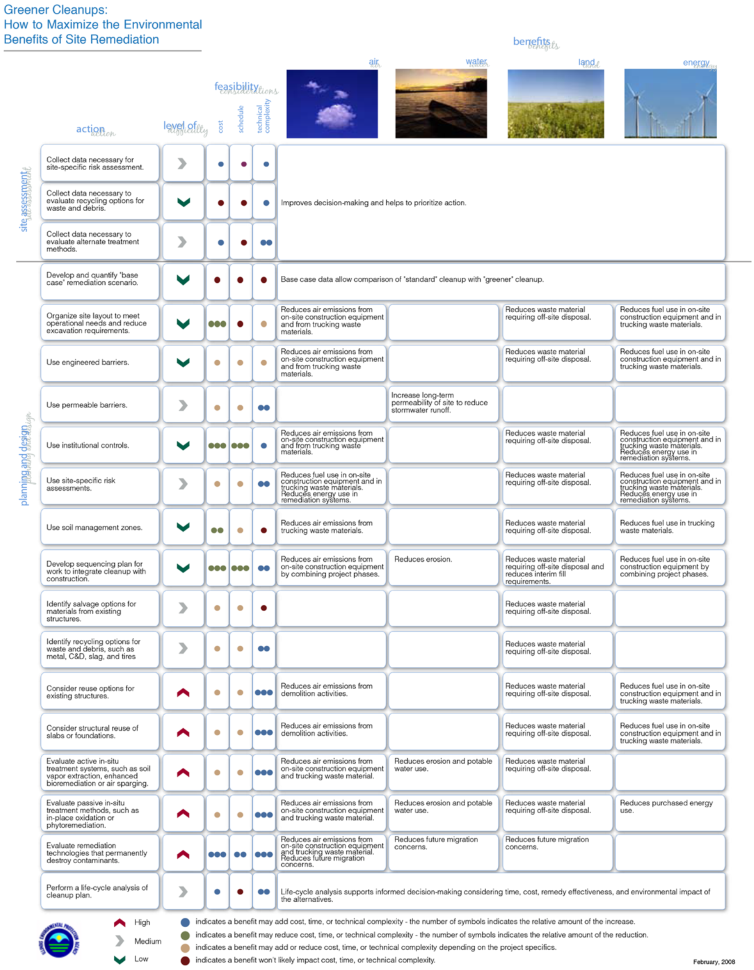
5.4.1.1 Illinois EPA Greener Cleanups Matrix

The Illinois EPA developed the Greener Cleanups Matrix to allow for an assessment of and to facilitate technology selection to optimize the direct and indirect benefit of remediation alternatives for the environment. The Matrix is based on five key principles: (1) ensuring every cleanup protects human health and the environment; (2) the integration of site reuse plans into the cleanup strategy, including project sequencing and appropriate inclusion of engineering and engineering controls into project design; (3) the conservation of raw materials such as soil and water and the salvage of building materials and other resources, with the goal of reducing waste disposal, reducing the use of virgin material inputs, and the use of existing infrastructure; (4) the conservation of energy, with an emphasis on the use of energy from renewable resources; and (5) the consideration of environmental effects associated with remediation alternatives, including contaminant fate and long-term stewardship responsibilities and consequences.

Using a multitiered approach that includes a simple matrix and a complex matrix, actions are identified that may be implemented during different phases of site remediation. The matrix assesses the relative impacts on air, water, land, and energy. It assesses the beneficial effect of BMPs but does not capture trade-offs associated with any BMPs. Based on the complexity of a given contaminated site under consideration, either the simple or complex matrix may be applied. Figure 5.1 provides a snapshot of the matrix, and the Illinois EPA website (Illinois EPA 2008) provides more information.

5.4.1.2 MPCA Tool Kit

The MPCA also developed a sustainability evaluation tool that specifically is used to identify and emphasize green practices for contaminated



Greener Cleanups:
How to Maximize the Environmental
Benefits of Site Remediation

	action	level of difficulty	feasibility considerations			benefits			
			cost	schedule	technical complexity	air	water	land	energy
site assessment	Collect data necessary for site-specific risk assessment.	›	🔵	🟣	🔵	Improves decision-making and helps to prioritize action.			
	Collect data necessary to evaluate recycling options for waste and debris.	⌄	🔴	🔴	🔵				
	Collect data necessary to evaluate alternate treatment methods.	›	🔵	🔴	🔵🔵				
planning and design	Develop and quantify "base case" remediation scenario.	⌄	🔴	🔴	🔴	Base case data allow comparison of "standard" cleanup with "greener" cleanup.			
	Organize site layout to meet operational needs and reduce excavation requirements.	⌄	🟢🟢🟢	🔴	🟤	Reduces air emissions from on-site construction equipment and from trucking waste materials.		Reduces waste material requiring off-site disposal.	Reduces fuel use in on-site construction equipment and in trucking waste materials.
	Use engineered barriers.	⌄	🟤	🟤	🟤	Reduces air emissions from on-site construction equipment and from trucking waste materials.		Reduces waste material requiring off-site disposal.	Reduces fuel use in on-site construction equipment and in trucking waste materials.
	Use permeable barriers.	›	🟤	🟤	🔵🔵		Increase long-term permeability of site to reduce stormwater runoff.		
	Use institutional controls.	⌄	🟢🟢🟢	🟢🟢🟢	🔵	Reduces air emissions from on-site construction equipment and from trucking waste materials.		Reduces waste material requiring off-site disposal.	Reduces fuel use in on-site construction equipment and in trucking waste materials. Reduces energy use in remediation systems.
	Use site-specific risk assessments.	›	🟤	🟤	🔵🔵	Reduces fuel use in on-site construction equipment and in trucking waste materials. Reduces energy use in remediation systems.		Reduces waste material requiring off-site disposal.	Reduces fuel use in on-site construction equipment and in trucking waste materials. Reduces energy use in remediation systems.
	Use soil management zones.	⌄	🟢🟢	🟤	🔴	Reduces air emissions from trucking waste materials.		Reduces waste material requiring off-site disposal.	Reduces fuel use in trucking waste materials.
	Develop sequencing plan for work to integrate cleanup with construction.	⌄	🟢🟢🟢	🟢🟢🟢	🔵🔵	Reduces air emissions from on-site construction equipment by combining project phases.	Reduces erosion.	Reduces waste material requiring off-site disposal and reduces interim fill requirements.	Reduces fuel use in on-site construction equipment by combining project phases.
	Identify salvage options for materials from existing structures.	›	🟤	🟤	🔴			Reduces waste material requiring off-site disposal.	
	Identify recycling options for waste and debris, such as metal, C&D, slag, and tires	›	🟤	🟤	🔵🔵			Reduces waste material requiring off-site disposal.	
	Consider reuse options for existing structures.	⌃	🟤	🟤	🔵🔵🔵	Reduces air emissions from demolition activities.		Reduces waste material requiring off-site disposal.	Reduces fuel use in on-site construction equipment and in trucking waste materials.
	Consider structural reuse of slabs or foundations.	⌃	🟤	🟤	🔵🔵🔵	Reduces air emissions from demolition activities.		Reduces waste material requiring off-site disposal.	Reduces fuel use in on-site construction equipment and in trucking waste materials.
	Evaluate active in-situ treatment systems, such as soil vapor extraction, enhanced bioremediation or air sparging.	⌃	🟤	🟤	🔵🔵🔵	Reduces air emissions from on-site construction equipment and trucking waste material.	Reduces erosion and potable water use.	Reduces waste material requiring off-site disposal.	
	Evaluate passive in-situ treatment methods, such as in-place oxidation or phytoremediation.	⌃	🟤	🟤	🔵🔵🔵	Reduces air emissions from on-site construction equipment and trucking waste material.	Reduces erosion and potable water use.	Reduces waste material requiring off-site disposal.	Reduces purchased energy use.
	Evaluate remediation technologies that permanently destroy contaminants.	⌃	🔵🔵🔵	🔵🔵	🔵🔵🔵	Reduces air emissions from on-site construction equipment and trucking waste material. Reduces future migration concerns.	Reduces future migration concerns.	Reduces future migration concerns.	
	Perform a life-cycle analysis of cleanup plan.	›	🔵	🔴	🔵🔵	Life-cycle analysis supports informed decision-making considering time, cost, remedy effectiveness, and environmental impact of the alternatives.			

⌃ High
› Medium
⌄ Low

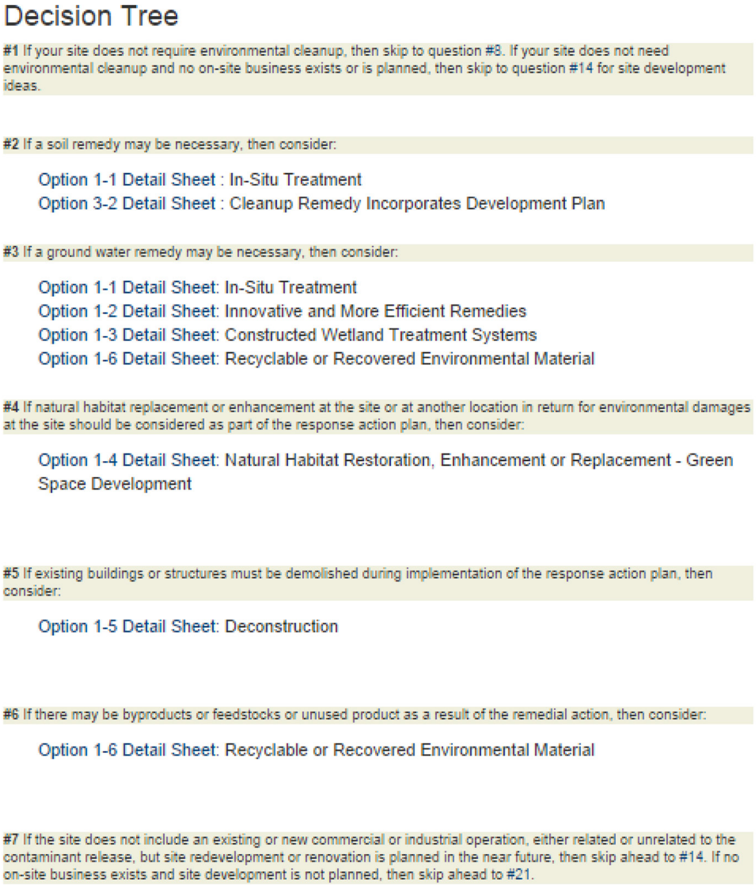
🔵 indicates a benefit may add cost, time, or technical complexity - the number of symbols indicates the relative amount of the increase.
🟢 indicates a benefit may reduce cost, time, or technical complexity - the number of symbols indicates the relative amount of the reduction.
🟤 indicates a benefit may add or reduce cost, time, or technical complexity depending on the project specifics.
🔴 indicates a benefit won't likely impact cost, time, or technical complexity.

February, 2008

Figure 5.1. Illinois EPA greener cleanups matrix.

site remediation (MPCA 2010). The tool also outlines how similar strategies may be applied for business operations as well as brownfield redevelopment. It includes a checklist of sustainability factors and includes a decision tree. The tool emphasizes the potential use of the following strategies: in situ treatment technologies; the use of innovative remediation approaches; the use of engineered wetlands for water treatment; restoration of natural habitats; allocation, enhancement, and protection of green spaces; deconstruction; and the use of recycled or reclaimed material.

The MPCA tool summarized the goal to achieve greener practices as a list of applicable regulatory guidelines. Additionally, the tool outlines site conditions where favorable applications of each of the six strategies may be successfully applied. Further, case studies outlining the application of the strategies are presented. Figure 5.2 shows an excerpt from the toolkit and more information can be found on MPCA's website.



Decision Tree

#1 If your site does not require environmental cleanup, then skip to question #8. If your site does not need environmental cleanup and no on-site business exists or is planned, then skip to question #14 for site development ideas.

#2 If a soil remedy may be necessary, then consider:

Option 1-1 Detail Sheet : In-Situ Treatment
Option 3-2 Detail Sheet : Cleanup Remedy Incorporates Development Plan

#3 If a ground water remedy may be necessary, then consider:

Option 1-1 Detail Sheet: In-Situ Treatment
Option 1-2 Detail Sheet: Innovative and More Efficient Remedies
Option 1-3 Detail Sheet: Constructed Wetland Treatment Systems
Option 1-6 Detail Sheet: Recyclable or Recovered Environmental Material

#4 If natural habitat replacement or enhancement at the site or at another location in return for environmental damages at the site should be considered as part of the response action plan, then consider:

Option 1-4 Detail Sheet: Natural Habitat Restoration, Enhancement or Replacement - Green Space Development

#5 If existing buildings or structures must be demolished during implementation of the response action plan, then consider:

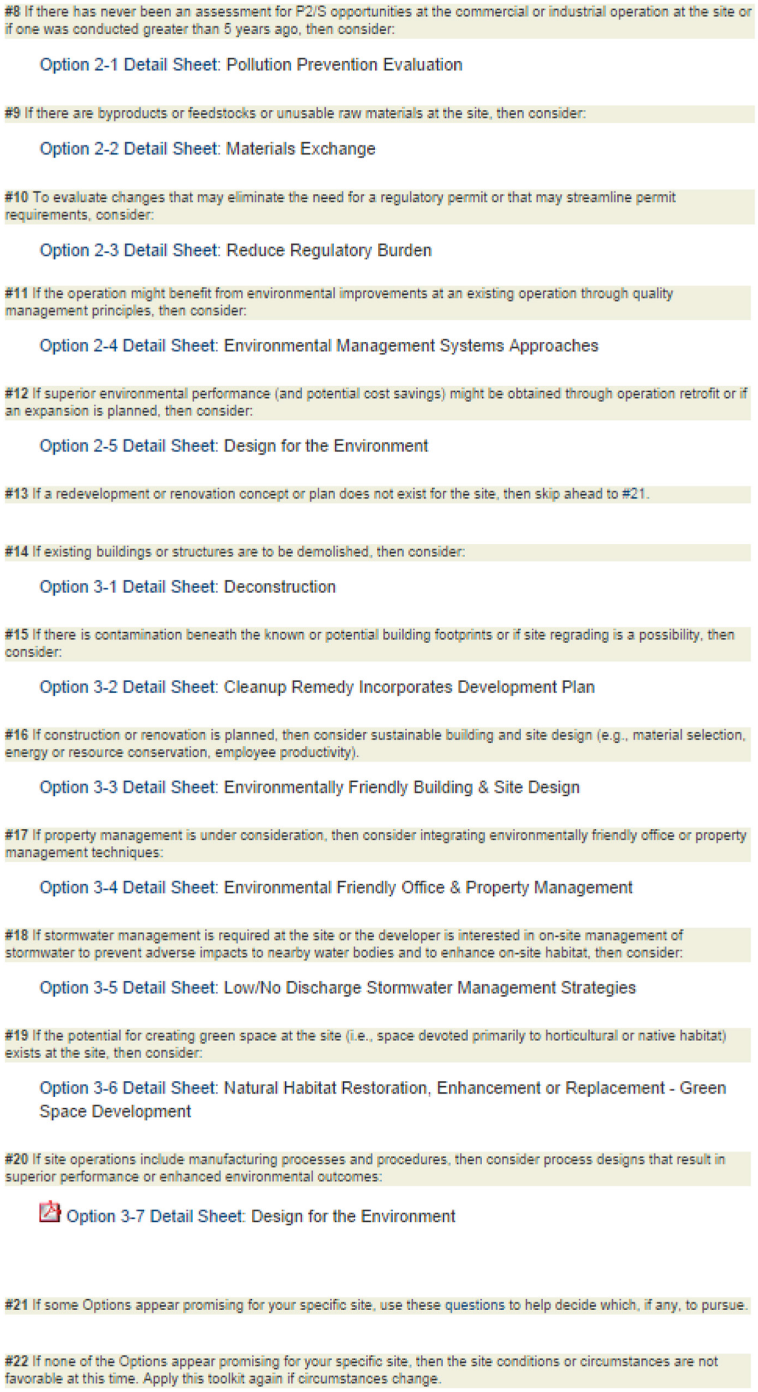
Option 1-5 Detail Sheet: Deconstruction

#6 If there may be byproducts or feedstocks or unused product as a result of the remedial action, then consider:

Option 1-6 Detail Sheet: Recyclable or Recovered Environmental Material

#7 If the site does not include an existing or new commercial or industrial operation, either related or unrelated to the contaminant release, but site redevelopment or renovation is planned in the near future, then skip ahead to #14. If no on-site business exists and site development is not planned, then skip ahead to #21.

Figure 5.2. Minnesota pollution control board sustainability evaluation tool. (*Continued*).



#8 If there has never been an assessment for P2/S opportunities at the commercial or industrial operation at the site or if one was conducted greater than 5 years ago, then consider:

Option 2-1 Detail Sheet: Pollution Prevention Evaluation

#9 If there are byproducts or feedstocks or unusable raw materials at the site, then consider:

Option 2-2 Detail Sheet: Materials Exchange

#10 To evaluate changes that may eliminate the need for a regulatory permit or that may streamline permit requirements, consider:

Option 2-3 Detail Sheet: Reduce Regulatory Burden

#11 If the operation might benefit from environmental improvements at an existing operation through quality management principles, then consider:

Option 2-4 Detail Sheet: Environmental Management Systems Approaches

#12 If superior environmental performance (and potential cost savings) might be obtained through operation retrofit or if an expansion is planned, then consider:

Option 2-5 Detail Sheet: Design for the Environment

#13 If a redevelopment or renovation concept or plan does not exist for the site, then skip ahead to #21.

#14 If existing buildings or structures are to be demolished, then consider:

Option 3-1 Detail Sheet: Deconstruction

#15 If there is contamination beneath the known or potential building footprints or if site regrading is a possibility, then consider:

Option 3-2 Detail Sheet: Cleanup Remedy Incorporates Development Plan

#16 If construction or renovation is planned, then consider sustainable building and site design (e.g., material selection, energy or resource conservation, employee productivity).

Option 3-3 Detail Sheet: Environmentally Friendly Building & Site Design

#17 If property management is under consideration, then consider integrating environmentally friendly office or property management techniques:

Option 3-4 Detail Sheet: Environmental Friendly Office & Property Management

#18 If stormwater management is required at the site or the developer is interested in on-site management of stormwater to prevent adverse impacts to nearby water bodies and to enhance on-site habitat, then consider:

Option 3-5 Detail Sheet: Low/No Discharge Stormwater Management Strategies

#19 If the potential for creating green space at the site (i.e., space devoted primarily to horticultural or native habitat) exists at the site, then consider:

Option 3-6 Detail Sheet: Natural Habitat Restoration, Enhancement or Replacement - Green Space Development

#20 If site operations include manufacturing processes and procedures, then consider process designs that result in superior performance or enhanced environmental outcomes:

Option 3-7 Detail Sheet: Design for the Environment

#21 If some Options appear promising for your specific site, use these questions to help decide which, if any, to pursue.

#22 If none of the Options appear promising for your specific site, then the site conditions or circumstances are not favorable at this time. Apply this toolkit again if circumstances change.

Figure 5.2. (*Continued*).

5.4.2 SEMIQUANTITATIVE ASSESSMENT TOOLS

While qualitative tools offer a screening tool of BMPs or other remediation-related factors, semiquantitative tools offer a greater degree of rigor and analysis. Typically, these tools will offer a *scorecard*-like approach in which potential quantitative factors may be ranked and scored, resulting in a weighted average or cumulative score that allows for a direct numerical comparison among several potential remediation alternative. These semiquantitative tools are typically straightforward and do not incorporate advanced numerical modeling; rather, they may be used for screening or feasibility assessment when considering remediation alternatives for a project as well as alternative applications for the design of a particular remediation technology that may have been selected for a project. Examples of semiquantitative assessment tools are presented in the following text.

5.4.2.1 California Green Remediation Evaluation Matrix

To encourage the use and incorporation of technologies and strategies that promote green remediation, the California Department of Toxic Substances Control (DTSC) created a semiquantitative assessment tool called the Green Remediation Evaluation Matrix (GREM). As shown in Table 5.2, it is a straightforward assessment tool based on an Excel platform that is used to comparatively assess remediation alternatives. The basic application of GREM is a qualitative matrix that is developed for a project site to be assessed. The matrix incorporates several site-specific parameters, including the extent and magnitude of contamination at the site, the potential existing and generated waste (including air pollutants and GHG emissions), potential physical disturbances and disruptions to the site and its vicinity, such as noise and traffic, and the consumption or restoration of resources. Additionally, several resources may be applied to the qualitative matrix such that it functions in a semiquantitative manner, including calculators for GHG emissions and energy consumption. LCA tools may also be applied to the GREM qualitative matrix. The tool may be applied to any or all activities across the life cycle associated with a remediation project.

5.4.2.2 Social Sustainability Evaluation Matrix

Using a similar matrix approach to GREM, Reddy, Sadasivam, and Adams (2014) developed a matrix for assessing the social dimensions of sustain-

Table 5.2. California GREM*

Stressors	Affected media	Mechanism and effect	Y/N **	Score
Substance release and production				
Airborne NO_x and SO_x	Air	Acid rain and photochemical smog		
Chloro-fluorocarbon vapors	Air	Ozone depletion		
GHG emissions	Air	Atmospheric warming		
Airborne particulates, toxic vapors, gases, or water vapor	Air	General air pollution, toxic air, or humidity increase		
Liquid waste production	Water	Water toxicity, sediment toxicity, or sediment		
Solid waste production	Land	Land use or toxicity		
Thermal releases				
Warm water	Water	Habitat warming		
Warm vapor	Air	Atmospheric humidity		
Physical disturbances and disruptions				
Soil structure disruption	Land	Habitat destruction and soil infertility		
Noise, Odor, vibration, or aesthetics	General environment	Nuisance and safety		

(*Continued*)

Table 5.2. California GREM* (*Continued*)

Stressors	Affected media	Mechanism and effect	Y/N **	Score
Traffic	Land; general environment	Nuisance and safety		
Land stagnation	Land; general environment	Remediation time; cleanup efficiency; redevelopment		
Resource depletion/gain (recycling)				
Petroleum (energy)	Subsurface	Consumption		
Mineral	Subsurface	Consumption		
Construction materials (soil, concrete, or plastic)	Land	Consumption and reuse		
Land and space	Land	Impoundment and reuse		
Surface water and groundwater	Water, land (subsidence)	Impoundment, sequester, and reuse		
Biology resources (plants, trees, animals, and microorganisms)	Air, water, land and forest, subsurface	Species disappearance or diversity reduction regenerative ability reduction		

*Use for evaluating one technology or remedial alternative as a checklist. Expand for alternative comparison by adding additional score columns for each alternatives.

**State whether the impact applies or does not apply to the alternative and continue the evaluation. DTSC Matrix (12/09).

ability. Known as SSEM, this tool assesses the social impacts that may be associated with a remediation project. The sustainability framework developed by the U.S. EPA (NRC 2011; U.S. EPA 2012), which incorporates an integrated approach for sustainability evaluation, formed the basis of SSEM. It is an Excel-based tool with several social dimensions and identified key measures, as presented in Table 5.3.

Table 5.3. Social dimensions and key theme areas included in the SSEM

Dimension	Key theme area
Socioindividual	Effect of proposed remediation on quality-of-life issues during and postconstruction or remediation
	Crime
	Cultural identity and promotion
	Overall public health and happiness
	Population demographics (age, income)
	Gender equity
	Justice and equality
	Care for the elderly
	Care for those with special needs
	Degree to which postremediation project will result in skills development
	Degree to which postremediation project will result in leadership development opportunities
	Enhancement of community or civic pride resulting in remediation and postremediation project
	Degree to which tangible community needs are incorporated in remediation design
	Transformation of perceptions of project and environs within greater community
	Potential of postremediation project to enhance cultural diversity in community
	Potential of incorporating newcomers to community
	Potential of remediation to foster better health through enhanced recreational opportunities
	Enabling knowledge management (including access to E-knowledge)

(*Continued*)

Table 5.3. Social dimensions and key theme areas included in the SSEM (*Continued*)

Dimension	Key theme area
Socioinstitutional	Appropriateness of future land use with respect to the community environment
	Degree of land use planning fostered by proposed construction or remediation
	Involvement of community in land use planning decisions
	Enhancement of commercial or income-generating land uses
	Improvement and enhancement of market-rate housing stock
	Improvement and enhancement of affordable housing stock
	Enhancement of recreational facilities
	Enhancement of the architecture and aesthetics of built environment
	Enhancement and participation of school system (i.e., new buildings) in community
	Enhancement and participation of new congregations and facilities in community
	Enhancement and participation of government institutions (i.e., new facilities) in community
	Degree of *grass-roots* community outreach and involvement
	Involvement of community organizations pre- and postconstruction and remediation
	Enhancement of cultural heritage institutions within community
	Involvement and enhancement of community-based charitable organizations
	Incorporation of green and sustainable infrastructure into construction and remediation
	Enhancement of transportation system improvements
	Trust, voluntary organizations, and local networks (also known as social capital)

Socioeconomic	Disruption of businesses and local economy during construction and remediation
	Employment opportunities during construction and remediation
	Employment opportunities postconstruction and remediation
	Degree of project investment toward local business entities (LBEs)
	Degree of project investment toward disadvantaged business entities (DBEs)
	Postconstruction and remediation third-party business generation
	Relative degree of increased tax revenue from site reuse
	Relative degree of increased tax revenue from nearby properties
	Degree to which green or sustainable or other *new economy* businesses may be created
	Degree of stimulated informal activities and economy
	Degree of anticipated partnership and collaboration with outside investors or institutions
Socioenvironmental	Remediation of naturally occurring contaminants (i.e., naturally occurring asbestos, radon)
	Remediation of anthropogenic contaminants at *chronic* concentrations
	Remediation of anthropogenic contaminants at *acute* concentrations
	Remediation of pervasive *economic poisons* or other pervasive conditions endemic in community
	Degree of protection afforded to remediation workers by proposed remediation
	Degree of disruption (noise, truck traffic) from proposed remedial method to the surrounding neighborhoods
	Degree of contaminant removal and destruction versus in-place capping or immobilization
	Degree of future characterization and remediation required by rezoning or altered land use

(*Continued*)

Table 5.3. Social dimensions and key theme areas included in the SSEM (*Continued*)

Dimension	Key theme area
	Greenness and sustainability of proposed remedial action
	Incorporation of green energy sources into remediation activity
	Restoration or impact to productive surface water or groundwater use
	Degree proposed remediation will affect other media (i.e., emissions and air pollution)
	Potential of future environmental impact (i.e., diesel exhaust from trucks)

SSEM incorporated meaningful, quantifiable factors related to social aspects associated with remediation projects, specifically cross-functional aspects of sustainability, including socioindividual, socioinstitutional, socioeconomic, and socioenvironmental aspects. Included in SSEM are 18 key measures for socioindividual impacts, 18 key measures for socioinstitutional impacts, 11 key measures for socioeconomic impacts, and 13 key measures for socioenvironmental impacts.

The socioindividual and socioinstitutional dimensions include indicators that pertain to overall impacts on standard of living, education, population growth, justice and equality, community involvement, and fostering local heritage. The socioeconomic dimension comprises indicators pertaining to business ethics, fair trade, and worker's rights. The socioenvironmental dimension accounts for the consumption of natural resources, environmental management, and pollution prevention associated with air, water, land, and waste materials. The incorporation of all four social dimensions and their corresponding indicators into the SSEM tool allows for an appropriate representation of the social impacts that may occur through the entire life cycle of a proposed environmental remediation project. The SSEM tool also allows for additional key areas to be incorporated to facilitate project-specific application and quantification of social impacts.

A scoring system is used in the SSEM as shown in Table 5.4. A zero value is assigned for activities with no impacts, +1 or +2 for positive impacts, and −1 or −2 for negative impacts. These are assigned to metrics associated with sustainability indicators under all four social dimensions.

Table 5.4. Scoring system for SSEM

Score				
Positive impact		**No impact or not applicable**	**Negative impact**	
Ideal	**Improved**		**Diminished**	**Unacceptable**
2	1	0	−1	−2

A score is assigned for each key factor, and the sums of scores for each dimension as well as the total score of all four dimensions are calculated. These values are then compared among remediation alternatives under consideration, including the *no action* option. This tool provides a better understanding of social impacts that may result from proposed remediation alternatives, which can facilitate the formulation of targeted action plans aimed at overall impact mitigation.

5.4.3 QUANTITATIVE ASSESSMENT TOOLS

For many projects, the use of a qualitative or semiquantitative analysis tool will prove to be useful for analyzing sustainability aspects of one or more remediation alternatives. This is especially the case when a project is relatively simple or straightforward, or when the tool is applied as a screening tool to assess the feasibility for a remediation project. In many instances, however, the results of a qualitative or semiquantitative analysis may be too limited to be of much use for sustainability analysis. This is especially the case for more complex remediation projects where a wide range of parameters need to be carefully and thoroughly assessed.

When warranted by the degree of complexity of a project, quantitative analysis tools should be incorporated for sustainability analysis. These advanced tools for sustainability evaluations typically offer a far more detailed and rigorous assessment of the environmental, social, and economic impacts of remediation. Because of their complexity, these tools require extensive data inputs with respect to a range of site-specific parameters. Some of the analysis tools are focused in their scope and intend to address one type of impact, such as carbon footprints or GHG emissions; other tools allow for comprehensive assessment across the environmental, economic, and social dimensions of sustainability. These tools can be used to evaluate sustainability impacts of different technologies, processes, or implementation methods at any stage of site cleanup, or may be applied from a life-cycle analysis approach assuming a variety of system boundaries. As with qualitative and semiquantitative analysis tools, some quantitative tools are in the public domain and are available free of charge; others are sold as for-profit software; still others are proprietary and limited to use within a particular organization. Table 5.5 presents and summarizes a range of quantitative tools, and several tools are described in the following text.

5.4.3.1 Sustainable Remediation Tool

SRT is a Microsoft Excel-based tool developed to assist environmental professionals in incorporating sustainability concepts with respect to remediation project decision making and design optimization. Developed by three corporations, AECOM, GSI Environmental Inc. and CH2MHill, on behalf of AFCEE, SRT has been explicitly listed as an analysis tool by several federal agencies for the sustainability analysis of potential remediation alternatives. SRT and related information are available via AFCEE's website.

SRT facilitates the optimization of existing remediation systems and allows for comparative evaluations of remediation approaches based on sustainability metrics. It also allows for the planning of future implementation of remediation technologies at a particular site. SRT calculates several key metrics, including atmospheric emissions (e.g., CO_2, NO_x, SO_x, and particulate matter [PM] with diameters less than 10 microns [PM_{10}]), total energy consumed, worker safety, and cost. The majority of these metrics may be monetized to allow for a cost analysis among alternatives. Normalized metrics also allow for a critical, objective assessment of various project alternatives. SRT also allows for the import of external costs and parametric data from Remedial Action Cost Engineering and Requirements (RACER™).

SRT is equipped to perform a sustainability analysis based on detailed site-specific input criteria for eight common soil and groundwater remediation technologies. Remediation technologies associated with soil include excavation, soil vapor extraction, and thermal treatment. Groundwater remediation technologies include pump-and-treat, enhanced in situ bioremediation, in situ chemical oxidation (ISCO), permeable reactive barriers (PRBs), and monitored natural attenuation (MNA). SRT may be implemented for Tier 1 analyses or more detailed Tier 2 analyses. The specific selection is based on the goal of the analysis as well as the degree and detail of input data used for the analysis.

Table 5.5. Summary of quantitative assessment tools

Tools designed for site remediation													
Title or common name	**Sponsor**	**General description and access information**	**Web calculator**	**Decision software**	**Decision matrix**	**Policy/industry tool**	**Site specific**	**Energy efficiency**	**Renewable energy**	**Water**	**Air emission**	**Land and ecosystem**	**Materials and waste**
Free to public													
ATHENA® impact estimator for Buildings and ATHENA® eco calculator for assemblies	Athena institute, university of Minnesota Green building initiative	Athena software evaluates whole buildings and assemblies based on LCA for material manufacturing, including resource extraction and recycled content; related transportation; on-site construction; regional energy use, transportation, and other factors; building type and assumed lifespan; maintenance, repair, and replacement effects; demolition and disposal; and operating energy emissions and precombustion effects. www.athenasmi.org/tools/impactEstimator		X			X	X		X	X	X	X

Building for environmental and economic sustainability (BEES)	National institute of Standards and technology (NIST), EPA environmentally preferable purchasing program	BEES 4.0 evaluates green building products categorized under 24 elements, taking into account U.S. methodology for U.S. life-cycle assessment. Evaluated impacts include global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, ozone depletion, water intake, criteria air pollutants, smog, ecological toxicity, cancerous effects, and noncancerous effects. To date, NIST has evaluated and scored over 230 products on BEES environmental and economic performance. The EPA Office of Resources Conservation and Recovery (ORCR) currently uses BEES model components to assess benefits associated with beneficial use of fly ash, ground granulated blast furnace slag, and silica fume in concrete building products. www.bfrl.nist.gov/oae/software/bees			X	X				X	X	X	X

Beneficial reuse model (BenReMod)	University of Toledo	The BenReMod is a suite of modules for comparing different materials that can be used for road construction in different scenarios. Modules address life-cycle assessment; human cancer and noncancer risk and ecological toxicity potential (for freshwater aquatic, terrestrial, and freshwater sediment systems); and a multicriteria decision analysis with an algorithm for ranking scenarios where no material consistently performs better. Model development continues, in part under an EPA Region 5 grant. http://benremod.eng.utoledo.edu/BenReMod		X			X	X		X	X	X	X
Diesel emissions quantifier	EPA	The quantifier can calculate emission estimates of NO_X, PM, hydrocarbons, CO, and CO_2 for a fleet of highway/nonroad vehicles or marine vessels with various diesel emissions control technologies. The tool supports diesel retrofit projects but is not designed to meet regulatory requirements for air or transportation reporting. An associated spreadsheet lists retrofit and clean diesel technology parameters. http://cfpub.epa.gov/quantifler/view/info.cfm, www.epa.gov/otaq/diesel/documents/appl-fleet.xls	X			X	X				X		

Economic input output-life cycle assessment (EIO-LCA)	Carnegie mellon-green design institute	The EIO-LCA contains a series of publicly available Web-based models that allow the user to estimate the overall environmental impacts from producing a certain dollar amount of any of 500 commodities or services in the United States. Most recent U.S. models (1997) reflect impacts in terms of 1997 U.S. dollars. www.eiolca.net		X		X	X	X	X	X	X	X	X
Energy and materials flow and cost tracker (EMFACT™)	Northeast waste management officials' association	EMFACT is designed to be used within companies for systematically tracking materials and energy use; releases, discharges, and wastes; and associated costs. The tool helps manufacturers to apply environmental management accounting when setting pollution prevention priorities, identifying value-added opportunities for sustainable production, and implementing materials and energy-efficiency improvements. www.newmoa.org/prevention/emfact/about.cfm		X			X	X		X	X		X
GREM	California DTSC	The GREM uses life-cycle thinking to evaluate treatment alternatives based on substance release/production, thermal releases, physical disturbances/disruptions, and resource depletion/gain (recycling). www.dtsc.ca.gov/OMF/Grn_Remediation.cfm			X		X	X		X	X	X	X

Greener cleanups matrix	Illinois department of environmental protection	The greener cleanups matrix helps maximize the environmental benefits of site remediation by evaluating the level of difficulty and feasibility (cost, schedule, and technical complexity) for actions associated with site assessment, planning and design, and cleanup. Matrix information is based on evaluation of certain cleanups from the Leaking Underground Storage Tank (LUST), Site remediation program (SRP), CERCLA, and RCRA programs using site-specific questionnaires, field visits, and consultations with green remediation practitioners. www.epa.state.il.us/land/greener-cleanups/matrix.pdf			X		X	X	X	X	X	X	X
Greenhouse gases, regulated emissions, and energy use in transportation (GREET)	DOE office of energy efficiency and renewable energy	GREET is a full life-cycle model to evaluate various vehicle and fuel combinations on a fuel-cycle or vehicle-cycle basis, including material recovery and vehicle disposal. For a given vehicle and fuel system, GREET calculates consumption of total energy (renewable and nonrenewable), fossil fuels, petroleum, coal, and natural gas; emissions of CO_2-equivalent GHG; and emissions of VOCs, CO, NO_X, PM_{10}, $PM_{2.5}$, and SO_X. The model includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems. www.transportation.anl.gov/modeling_simulation/GREET/index.html		X		X	X	X	X		X		X

Greenscapes	EPA	This suite of tools includes six spreadsheet-based calculators for use in GreenScapes project decision making and cost comparisons regarding virgin materials versus environmentally preferable products or methods. Individual calculators address recycling and reusing landscape waste, resource conserving landscaping cost, erosion control, decking cost, subsurface drip irrigation cost, and pallets cost. www.epa.gov/epawaste/conserve/III/greenscapes/tools/index.htm		X		X				X		X	X
Hybrid2	DOE national renewable energy laboratory, university of Massachusetts	The Hybrid Power System Simulation Model (version 2) simulates performance of renewable energy systems involving combinations of different electrical loads, types of wind turbines, photovoltaics, diesel generators, battery storage, and power conversion devices. The tool also compares long-term performance of comparable systems. www.nrel.gov/applying_technoloaies/engineering_finance.html		X			X		X				
Industrial waste management evaluation model (IWEM)	EPA	IWEM software helps determine the most appropriate waste management unit design to minimize or avoid adverse groundwater impacts. Evaluation parameters include liner types, hydrogeologic conditions of a site, and toxicity and expected leachate concentrations from anticipated waste constituents. IWEM lookup tables cover approximately 60 organic or inorganic constituents with established maximum contaminant levels. www.epa.gov/epawaste/nonhaz/industrial/tools/iwem/index.htm		X			X			X		X	

PaLATE model	University of California-Berkeley	The PaLATE model is an environmental life-cycle model for the transportation sector. EPA's ORCR currently uses the tool to assess benefits for reuse of industrial materials such as fly ash, foundry sand, construction and demolition debris in concrete pavement, asphalt pavement, and road base. www.ce.berkeley.edu/~horvath/palate.html			X	X				X	X		X
Performance tracking tool (PTT)	AFCEE	A simple Excel-based tool to evaluate systems to find whether contaminant rate removal is consistent with projected reduction rates and project costs. Using normalized data to graphically display the results, one can easily visualize the understanding of system operations with respect to existing environmental conditions. PTT can assist in decision making from the existing site-specific data by helping identify system end points in the remediation process, revise extraction points as needed, evaluate effects of remedial decisions, and then adjust accordingly to enhance the efficiency of the systems. www.afcee.af.mil/shared/media/document/AFD-100113-032.xls		X			X	X		X		X	X

RET screen	Natural resources Canada	RETScreen evaluates energy production and savings, costs, emission reductions, financial viability, and risk for various types of renewable-energy and energy-efficient technologies. The tool includes product, project, hydrology, and climate databases; a user manual; and a case study-based college/university-level training course. Companion information includes a training course on legal aspects of energy projects. www.retscreen.net		X			X	X	X				
SiteWise sustainable environmental restoration tool	Battelle, U.S. Navy, and USACE	SiteWise, a sustainable environmental remediation tool, is designed to calculate the environmental footprint of remedial alternatives generally used by the industry. The tool is a series of Excel sheets and currently provides a detailed baseline assessment of several quantifiable sustainability metrics including GHGs; energy usage; criteria air pollutants, including SO_X, NO_X, and PM; water usage; and accident risk. The tool is being jointly developed by Battelle, U.S. Navy, and USACE and expected to be available as freeware in spring 2010. (Battelle point of contact: Mohit Bhargava)		X			X	X	X	X	X		X

SRT	AFCEE	The SRT is designed to evaluate particular remediation technologies on the basis of sustainability metrics. The tool, programmed in Microsoft Office Excel®, facilitates sustainability planning and evaluation, which is intended to aid environmental professionals in achieving remedial process optimization goals and complying with regulations (e.g., EO 13423, which affects department of defense [DOD]). The SRT allows users to estimate sustainability metrics for specific technologies for soil and groundwater remediation. The current technology modules included in the SRT are excavation, soil vapor extraction, pump and treat, and enhanced bioremediation. Additional technologies and metrics are under development. For each technology and in each tier of evaluation, the following sustainability metrics are calculated: GHG emissions, total energy consumed, technology cost, safety and accident risk, and natural resource service. The SRT is structured into two levels of input complexity. Tier 1 calculations are based on rules-of-thumb information that are widely used in the environmental remediation industry. Tier 2 calculations are more detailed and incorporate site-specific factors. The output metrics are presented in both a nonnormalized and a normalized/cost-based format. www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sustainableremediation/index.asp		X			X	X		X	X	X	X

Waste reduction model (WARM)	EPA	EPA's ORCR uses WARM to assess benefits of the Waste Wise program and specific benefits from reusing material such as fly ash, municipal solid waste recycling matter, and yard trimming compost (as a proxy for GreenScapes benefits). WARM also helps the public estimate GHG reductions of different waste management practices such as source reduction, recycling, combustion, composting, and landfilling for (currently 34) material types. epa.gov/climatechange/wycd/waste/calculators/Warm_home.html	X			X					X		X
Proprietary/restricted													
BalancE3™	ARCADIS	BalancE3 is a quantitative, Web-based tool used to evaluate different GSR approaches and incorporate them in remedy evaluation, selection, and design on a site-specific or portfolio-wide basis. It aggregates diverse sustainability metrics; provides the flexibility to prioritize any combination of eight metrics (energy, air emissions, water requirements, land impacts, waste generation and material consumption, long-term stewardship, health and safety, and life-cycle costs) for a given analysis; applies statistical methods and trade-off analyses to facilitate alternatives comparison; identifies key metrics to improve remedies through the practical application of greener remediation concepts; and provides a solution to calculate and manage carbon. (Point of contact: Kurt Beil, ARCADIS U.S. Inc., Newtown, PA)	X	X			X	X		X	X	X	X

Boustead model	Boustead consulting Ltd.	The Boustead Model is a tool for life-cycle inventory calculations of industrial processes. Version 5 links site-specific input to core data on fuel production, materials processing, stand-alone aspects, air emissions, water emissions, solid waste, solid waste regulated by the European Union, raw materials, fuels, feedstocks, and activity functions. www.boustead-consulting.co.uk/introduc.htm					X	X		X	X	X	X
Clean me green	Malcolm Pirnie, Inc., University of California-Santa Barbara Bren School of environmental science and management	This spreadsheet tool was developed to improve the sustainability of site remediation by quantifying the cost, energy, and carbon savings associated with selecting or optimizing different remedial technologies. Use of this tool promotes creative and sustainably oriented thinking and emphasizes the benefits associated with greener approaches to remediation (Points of contact: Maryline Laugier and Elisabeth Hawley, Malcolm Pirnie)		X			X	X	X	X	X		
Cleanup Sustainability Framework	DuPont, EPA Region 3	The framework was developed under a pilot project to evaluate sustainability of potential remedies and identify the optimal remedy at three RCRA sites in EPA Region 3. Metrics of a related credit/debit system focus on CO_2 equivalents, energy consumption, water use, soil use/ disposal, material use, and land. (Points of contact: Deb Goldblum, EPA Region 3 and David Ellis, DuPont)			X		X	X		X	X	X	X

GaBi	PE consulting (Germany)	Originally developed by the University of Stuttgart, GaBi now is a commercially available suite of software and databases for life-cycle assessment (ISO 14040/44), carbon footprints (PAS 2050), GHG accounting, designs, energy efficiency, green supply chains, and material flow analysis. Software/database cost information is available through direct inquiries. www.gabi-software.com		X			X	X			X		X
GoldSET	Golder Associates Ltd.	GoldSET assesses the sustainability performance of remedial options based on site-specific scoring and weighting of environmental, social, and economic impacts. Over the past three years, GoldSET has been used in the United States, Canada, and Australia by the public and the private sectors. It is presently being customized to the requirements of a large corporation as well as for a Canadian federal agency, www.gold-set.com	X	X	X		X	X	X	X	X	X	X

Green remediation analysis	EPA region 9	Green remediation analysis is a spreadsheet tool for quantifying the environmental footprint of a remedy, using a life-cycle assessment approach. The spreadsheet tool may be used to compare alternative remedies at a cleanup site or to identify opportunities for reducing the environmental footprint of an existing remedy. Analytical parameters include resource use (fresh water, construction materials, remediation materials, gasoline and diesel fuel, and electricity), air emissions (CO_2, NO_X, SO_X, particulates, and air toxics), solid and hazardous waste generation, and wastewater discharge. Off-site manufacturing and transport are included in the analysis. Pilot testing of the spreadsheet tool is under way at three cleanup sites. When pilot testing is completed, the spreadsheets are intended for use by regulators, their contractors, and regulated site owners at other cleanup sites. (In development, point of contact: Karen Scheuermann. EPA region 9)					X	X		X	X		X

Green remediation spreadsheets	EPA	This methodology considers contributions to the footprints from multiple components of remedies, including site investigation, construction, operations and maintenance and long-term monitoring. Both on- and off-site activities associated with each remedy component are included in the study. The method documents a process for estimating the footprints, provides the library of resources and reference values used in the study, documents findings specific to the evaluated remedies, and presents both site-specific and more generalized observations and lessons learned from conducting the study. Other primary objectives include, but are not limited to the following: • Identifying or developing appropriate and applicable "footprint conversion factors" to calculate the footprints from various types of energy, materials, and services used in the remedy; • Estimating the footprints of up to 15 environmental parameters for three remedial alternatives; • Estimating the contribution to the various footprints from on-site activities, transportation, and nontransportation off-site activities;			X		X	X	X	X	X	X	X

		• Identifying those components of the various remedial alternatives that have a significant effect on the environmental footprint and those components that have a negligible effect on the environmental footprint; and • Conducting a sensitivity analysis for variations in the remedy design information, footprint conversion factors, or other input values											
Sustainability assessment framework	CH2M Hill	The Sustainability Assessment Framework and methodology tool helps with both tasks by providing a framework for identifying sustainability criteria and a methodology for evaluating the greatest value sustainability options for the customer. This framework helps decision makers select from a universe of potential sustainability metrics (over 100) and includes a decision-making tool that facilitates input of life-cycle inventory information that can be integrated into a analytical hierarchy process for decision making and stochastic assessment of uncertainties. The decision-making process can be used for sustainability decisions alone or be used to integrate sustainability decisions with other project decision factors. (Point of contact: Paul Favara, CH2M Hill)		X	X	X	X	X	X	X	X	X	X

Net Environmental Benefit Analysis (NEBA)	DOE Oak Ridge National Laboratory, EPA national center for environmental assessment, CH2MHill	NEBA is a risk management tool for evaluating trade-offs associated with environmental response actions. The tool can be supplemented with the nine NCP remedy selection criteria to evaluate site cleanup benefits related to increases in human use value, ecological service value, and economic value to society. (Points of contact: Rebecca Efroymson, Oak Ridge National Laboratory; Glenn Suter, NCEA; and Paul Favara, CH2M Hill)			X		X	X	X	X	X	X	X
SimaPro	Product ecology consultants	SimaPro is LCA software which collects, analyzes, and monitors the environmental performance of products and services. The tool can model and analyze complex life cycles in a systematic and transparent way, following the ISO 14040 series recommendations. www.pre.nl/simapro/simapro_lca_software.htm		X	X	X	X	X	X	X	X	X	X
Sustainability assessment tool	BP	This tool evaluates sustainability of existing remedies at specific sites. The tool has been used to evaluate remediation technologies such as (but not limited to) soil vapor extraction and pump and treat at an urban service station and sludge-pit treatment at a Superfund site in Texas. (In development, Point of contact: Stephanie Fiorenza, BP)			X		X			X	X	X	

Sustainable principles for site remediation	Good earth-keeping organization, inc.	This commercial framework helps improve the efficiency of soil vapor extraction and multiphase extraction systems, with a focus on alternative methods for off-gas treatment. (In development, Point of contact: Lowell Kessel, Good Earth-Keeping Organization, Inc.)			X		X	X			X		
Sustainable remediation assessment tool	Haley & Aldrich	This tool evaluates the sustainability impacts of different remediation alternatives throughout a remediation project life cycle (including potential site redevelopment) and subsequently provides recommendations to reduce sustainability impacts. The tool addresses environmental, social, and economic impact indicators, for example, GHG emissions, criteria pollutant emissions, ecosystem disturbance, water consumption, natural resource use, solid waste production, impacts to the local community/environmental justice, occupational risk, transportation risk, and total cost of remediation. (In development, Point of contact: Karin Holland, Haley & Aldrich, Inc.)		X			X	X	X	X	X	X	X
Sustainable remediation: cost and benefit analysis (CBA)	Shell global solutions (UK)	The CBA tool provides a risk-based framework to help balance decision making during remedy selection, with a focus on finding the economic optimum. (In development, Point of contact: David Reinke, Shell Global Solutions)			X		X	X		X	X	X	X

Tool for the reduction and assessment of chemical and other environmental impacts (TRACI)	EPA office of research and development	EPA developed TRACI to assist in impact assessment for sustainability metrics, life-cycle assessment, industrial ecology, process design, and pollution prevention. The LCA process may include both the consideration of material and energy inputs and outputs and the impacts associated with the emissions related to these material and energy flows. An example of one such model is TRACI. Impacts fit generally into two categories: 1. Depletion: impacts related to resource, land, and water use; and 2. Pollution: impacts related to ozone, global warming, smog, human and ecotoxicology, acidification, eutrophication, radiation, waste heat, odor, and noise. Many emissions or factors related to remediation, such as diesel emissions, fugitive VOCs, emissions associated with electricity production, methane emissions, as well as emissions associated production of materials and treatment chemicals, can be associated with these impact categories www.epa.gov/nrmrl/std/sab/traci		X			X			X	X	X	X

Source: ITRC (2011).

5.4.3.2 CleanSWEEP

AFCEE has also developed a tool called *CleanSWEEP* (Clean Solar and Wind Energy in Environmental Programs) for assessing alternative energy use at remediation sites. As with SRT, CleanSWEEP is an Excel-based analysis tool available for free via AFCEE's website. CleanSWEEP evaluates the two most common forms of renewable energy, photovoltaic-solar panel systems and wind energy systems, and uses existing Department of Energy (DOE) data to estimate solar and wind potential and related efficiency or efficacy in applying renewable energy systems. Remediation systems with low energy requirements over long periods as well as those systems that do not require continuous operation, remediation applications in remote locations, and remediation systems with power requirements of 1 kW to 20 kW are appropriately analyzed using CleanSWEEP. It is best applied to inform design-related decisions of small- to mid-sized remediation systems, but may also be used as a screening tool for large and complex systems as well as an analysis alternative to sustainability evaluation tools.

5.4.3.3 SiteWise

Similar to SRT and CleanSWEEP, SiteWise is an Excel-based sustainability assessment tool used for the sustainability analysis of remediation project alternatives. It provides an assessment of several quantitative metrics, including CO_2, NO_x, SO_x, and PM_{10} emissions; energy consumption, water consumption, and resource consumption; and worker safety. Developed by the U.S. Navy in partnership with the U.S. Army, the U.S. Army Corps of Engineers, and Battelle Memorial Institute, SiteWise is available via the *Green and Sustainable Remediation* portal on the U.S. Navy's website (NAVFAC 2011).

Analyses are performed on SiteWise by dividing each project remediation alternative under consideration into four phases: (1) remedial investigation, (2) remedial action construction, (3) remedial action operations, and (4) long-term monitoring and maintenance. Activities associated with each phase that may have an effect on the environment are incorporated into the analysis as inputs. Some activities include but are not limited to transportation of material and labor, material production, equipment operation, and waste management.

The quantitative impacts associated with the user-provided inputs are derived from publically available tables and databases. Additionally, SiteWise identifies potential technologies, such as renewable energy sources or energy-saving equipment that may be incorporated into a remediation alternative. It also allows for a cost-benefit analysis of such considerations.

Once each project remediation alternative is broken down into the four phases described earlier, the environmental impact of each phase may be calculated. The impacts may be grouped for cumulative impacts by one or more phases or across the entire remediation project cycle. Ultimately, the total cumulative impacts are calculated, allowing for an objective comparison among remediation project alternatives under consideration.

This phase-based analysis approach allows for easier identification of phases or entire remediation alternatives that result in greater relative impacts. This allows for optimized design on a phase-by-phase basis, or the potential to implement hybrid approaches that reduce impacts. It may also reduce redundancy with respect to the sustainability analysis process in multiple alternatives that have identical phases or subphases.

5.4.3.4 U.S. EPA Environmental Footprint Analysis Tools

Within its green remediation framework, the U.S. EPA has developed an environmental footprint assessment tool. The purpose of this tool is to quantify environment-related impacts (*environmental footprint*) associated with remediation projects undertaken to meet regulatory cleanup goals and requirements such that actions may be undertaken to lessen or minimize environmental impacts. The dual goals of the environmental footprint tool are to identify meaningful environmental metrics for quantification while concurrently establishing a methodology for the quantification of these metrics. The metrics identified and incorporated into this tool are aligned with U.S. EPA's five core elements of green remediation (U.S. EPA 2011). The tool focuses on a project's carbon footprint (i.e., the quantification of CO_2 emissions associated with a project), but it may also be used to calculate the environmental impacts associated with other parameters, including NO_x, SO_x, and PM_{10} emissions, energy use, water use, and land use. The tool may be used to design and optimize a particular remediation alternative or comparison and selection of an alternative among several remediation alternatives under consideration.

With specific respect to carbon footprint analysis, several tools have been developed with different emphasis on a range of factors and system boundary implementation. The U.S. EPA has also developed a tool specifically used to calculate GHG emissions associated with waste management practices. The WARM (U.S. EPA 2010) may be used to calculate GHG emissions associated with various waste management practices across a wide range of municipal solid waste materials. Some applicable practices include source reduction, recycling, composting, combustion, and landfilling.

WARM calculates reduced GHG emissions resulting from the applications of several activities or technologies, including the following:

- Energy conservation or use reduction measures
- The incorporation of renewable energy sources
- Reductions in fuel use
- The use of greener energy sources when zero emission sources cannot be used
- Green chemistry measures, including materials substitution
- Water conservation or reduced water use
- Management of material inputs and waste streams

WARM applies emission factors from the Climate Registry (The Climate Registry 2009), from U.S. EPA's Climate Leaders GHG Inventory Protocol Core Module Guidance, and from published reports. These factors are used to derive energy and CO_2 equivalent units for a variety of material inputs and outputs.

5.4.3.5 Life-Cycle Assessment

As mentioned previously, when considering the most appropriate sustainability tool for a given project, it is important to consider the degree of complexity regarding the project with respect to its parameters across the various sustainability dimensions. When a complex project is under consideration, or when a comprehensive analysis is desired, an LCA is often a useful and desirable assessment tool. The International Organization for Standards (ISO) developed a standard for performing LCA. It defines LCA as the "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle." The ISO's definition of *product* also includes services; therefore, remediation (a service) may be incorporated into an LCA analysis.

An LCA is most appropriate when a project under consideration will utilize a wide range of material, capital, and labor inputs, has the potential to generate significant or wide-ranging outputs with associated impacts, or when metrics are desired or required to be measured across a wide range of indicators. It provides a method for evaluating the total impacts a product (or service) may cause to the environment over its entire existence, or *cradle to grave*, beginning with initial manufacturing processes and ending with disposal or final disposition. When applied to a remediation project, LCA may analyze and incorporate the effects of manufacturing, transportation, use, and disposal of different materials and products associated with that activity. This includes accounting for energy and resource inputs as well as emissions and waste generations that affect land, water, and air. LCA can take into account direct and indirect impacts during all phases of a remediation project, including site characterization, system installation and optimization, system operation, maintenance, monitoring, postremediation monitoring, and impacts associated with subsequent productive land use. In assessing and optimizing a remediation alternative with respect to sustainability, LCA can be used to identify the best approach for minimizing natural resource use, means to incorporate renewable or reclaimed materials and energy sources, rehabilitation of land for productive use, natural habitat protection or restoration, and cost-benefit analysis with respect to financial and temporal dimensions. An LCA analysis may be used to assess existing remediation systems, identify opportunities to decrease impacts in future remediation applications, identify optimal conditions where a specific remediation system may be applied, or compare and evaluate different remediation alternatives.

In general, an LCA follows a framework that includes the following steps:

- Definition of analysis scope, goals, and key assumptions to be incorporated;
- Performance of an inventory analysis, which includes the development of a process flow chart, system boundary definition, data collection, and data processing;
- Assessment of impact, including classification, characterization, and valuation;
- Interpretation of assessment results; and
- Identification of means of improvement for the remediation project alternative under consideration with respect to sustainability-related metrics and indicators.

Several resources have been developed that provide guidance with respect to LCA use; some of these include ISO 14044 (ISO 2006), SURF Guidance for Footprint Assessments and LCAs (Favara et al. 2011), U.S.

EPA's LCA: Principles and Practice (U.S. EPA 2006), and U.S. EPA's Methodology for Understanding and Reducing a Project's Environmental Footprint (U.S. EPA 2012).

When performing an LCA, it is essential to carefully consider the system boundary. It should be selected in a way that parameters that have a negligible or immaterial effect on overall impacts may be eliminated, but it is important to use a boundary that captures enough impacts such that the assessment may be meaningful and provide useful detail. For example, the complex extreme would assume a *cradle-to-grave* scenario in which all related activities from initial raw material extraction to final disposal would be accounted. Of course, this may be useful for some assessment scenarios but unnecessarily complex for many other analyses. As a simpler example, the system boundary may account only for the physical implementation of a remediation project and look only at inputs and outputs that are directly applied and emanate at the project site during operation. Additionally, data used for an LCA analysis may be complex, expensive, or difficult to acquire.

Regardless of the selected boundary and processes under consideration of the analysis, the following should be included:

- Equipment
- Consumable materials
- Personnel
- Natural resources
- Energy inputs used during implementation, operation, monitoring, and so forth; both directly by the remediation system as well as that consumed by the other categories listed

Several LCA analysis tools have been reported, but two LCA tools in particular are in widespread use. SimaPro is a for-sale application developed by Product Ecology (Pré) Consultants. It may be used to calculate carbon footprint and other environmental impacts as well as key processes that may drive performance improvement with respect to sustainability. Several emissions inventory sources, both based on U.S. and international data, may be utilized during application. Additionally, SimaPro utilizes numerous impact assessment methods that may be used to group impacts into receptor-specific categories.

GaBi Software® (PE International 2011) is an LCA software package developed by PE International. A Free version of GaBi (GaBi Education) is available for selective academic use. GaBi offers functionality similar to SimaPro and may be used to perform evaluations similar to those generated by SimaPro.

When conducting an LCA, data is compiled and inventoried. The resulting life-cycle inventory and associated parameter(s) are assigned to one or more impact categories and are typically reported following conversion into equivalent unit, generally by multiplying by a normalization factor. The specific impact categories that may be used during an analysis are specific and dependent on the tool being used for the analysis. One example is the U.S. EPA's TRACI. This assessment inventory tool, utilized by several LCA tools, includes the following nine impact categories (from EPA's TRACI website and Bare [2011]):

- Global Climate Change impact category—reported as carbon dioxide (CO_2) equivalents
- Acidification impact category—reported as sulfur dioxide (SO_2) equivalents
- Eutrophication impact category—reported as nitrogen (N) equivalents
- Ozone depletion impact category—reported as trichlorofluoromethane (CFC-11) equivalents
- Photochemical smog formation impact category—reported as ozone (O_3) equivalents
- Human health particulate matter (PM) impact category—reported as fine particulate matter ($PM_{2.5}$) equivalents
- Human health cancer impact category—reported as comparative toxicity unit cancer (CTU cancer) equivalents
- Human health noncancer impact category—reported as comparative toxicity unit noncancer (CTU noncancer) equivalents
- Ecotoxicity impact category—reported as comparative toxicity unit ecotoxicity (CTU eco) equivalents

Other impact categories, such as those associated with renewable energy and nonrenewable energy use, may also be incorporated into an assessment when permissible by the LCA tool that is being used for an analysis.

The resulting converted parameters are added for each respective impact category, and results are presented in terms of indicator equivalents. Once the cleanup's impact assessment is complete and results are presented for each of the impact categories, the impact categories can be mapped to a related core element or elements. As an example, particulate matter may be mapped to a human health core element as well as a surface soil core element (due to aerial deposition).

5.5 SELECTION OF TOOLS FOR SUSTAINABILITY EVALUATIONS

The tools presented are applicable to projects with a wide range of scope and complexity. No single tool option can cover every type of project. Rather, it is important to assess several key aspects of a project, which can then be used to select the most appropriate tool for analysis. First, in some cases, a tool may be recommended or required by the specific regulatory agency that is providing oversight for the remediation project. Sometimes the agency has developed a tool, in other cases there is a formal or informal agency endorsement, and in still other cases a specific case officer may have a familiarity or preference for a specific tool. Also, the size, scope, and relative degree of complexity are a major factor to consider during tool selection. Generally speaking, smaller, less complex remediation projects will often focus on the incorporation of BMPs. The desired phase or phases of a remediation project that warrant analysis can also influence tool selection; some tools are more appropriate for certain aspects of a given remediation project. Larger, more complex projects will often necessitate the use of increasingly powerful but complex tools. Additionally, the desired sustainability metrics to be measured can influence tool decision. Prior to selection, a list of important or relevant metrics should be identified, and then tools that are able to provide an assessment of these desired metrics may be selected. Finally, some tools offer detailed analyses for specific remediation-related technologies. While these analysis tools are very powerful and offer great detail, their application is limited to the specific remediation technologies for which they have been developed. Obviously, the analysis tool can only be selected if the corresponding remediation technology will be implemented.

Once one or more potential analysis tools have been identified, there are several operational practices that should be considered when performing the analysis. First, the analysis should be kept as simple as possible, but it should, of course, provide the appropriate level of detail to be meaningful and useful. This includes selection of the tool, which, as mentioned earlier, generally follows that simpler tools may be applied to simpler projects, while more complex projects require more complex tools. Second, it is important to maintain objectivity and transparency during tool application. This includes justification for inputs and parameters. Simply stated, objectivity and transparency make it easier to achieve buy-in and concurrence for a particular study from a range of project stakeholders. Finally, it is good practice to perform sensitivity analyses of the analysis process and the results of the analyses. The sensitivity analysis can provide insight regarding the relative weight of key inputs and parameters and how deviations associated with uncertainty may affect results. Several analysis tools actually have sensitivity analysis capabilities.

5.6 SUMMARY

Several frameworks may be used to evaluate the sustainability of a remediation project across one or more of the dimensions of sustainability: environmental, economic, and social aspects. However, key indicators also should be identified, and each indicator should be expressed by a metric to measure the sustainability of remediation projects. Several tools have been developed to compute the metrics and provide a means for objective evaluation.

Sustainability metrics may be grouped in the order of increasing difficulty for application: (1) number of BMPs, (2) semiquantitative tools, and (3) quantitative tools. The key considerations for selecting the appropriate tool include the following: the regulatory agency involved in a cleanup program, the size of the remediation project, the site remediation phase, selected sustainable remediation metrics, and available technologies.

There are several best practices to keep in mind during any sustainable remediation evaluation, including the following: the use of the simplest level of sustainable remediation evaluation that is needed to meet sustainable remediation goals, transparency during the sustainable remediation process, and the benefit of uncertainty analysis of sustainable remediation results.

CHAPTER 6

CASE STUDIES

6.1 CASE STUDY 1: CHICAGO INDUSTRIAL SITE

6.1.1 PROJECT BACKGROUND

The project site measures approximately 117 acres and consists of a vacant and wooded marshland. Slag or fill materials and fly ash associated with past illegal dumping activities have been identified at the site. The properties surrounding the site have been heavily industrialized since the late 1800s; current and historic land uses near the site include heavy manufacturing, underground storage tank usage, landfills, and illegal dumping. The site is planned to be used as an ecological open space reserve with public hiking trails (City of Chicago 2005).

The site investigations revealed that site geology consists of nonnative vegetative soil cover (loamy soil consisting of a mixture of sand, silt, and clay), sandy blue-green fill (solid waste facility fill material consisting of sand and slag), native soils (well-sorted sand and silty clay), and a bedrock layer of dolomite and limestone at depths greater than 30 feet below the ground surface. Figure 6.1 depicts the typical soil profile of the site. The site has a surficial silty sand aquifer underlain by silty clay glacial till of low permeability serving as an aquitard. Estimated depth to the first occurrence of groundwater is approximately one to five feet below ground surface. Based on the topographical gradient, the hydrological gradient is inferred to be directed toward the east, although the groundwater flow direction and the depth to shallow, unconfined groundwater would likely vary depending upon seasonal variations in rainfall and other hydrological features.

Soil, surface water, sediment, and groundwater samples at various locations throughout the site were analyzed for the presence of volatile organic compounds (VOCs), polynuclear aromatic hydrocarbons (PAHs), pesticides, metals, total organic content, and pH. Contamination was

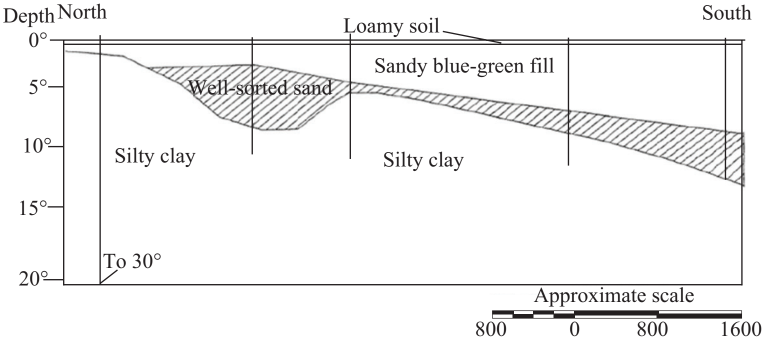


Figure 6.1. Soil profile at the site.

pervasive throughout the entire site. In the vadose zone, soils are predominantly fill materials and are contaminated by PAHs, pesticides, and metals at various locations from an average depth of zero to four feet. Groundwater is contaminated with lead or selenium at select locations. Contaminants in the surface water were found to be below the regulatory levels of human and ecological risk.

A risk assessment was performed to quantify the threat posed to human health and environmental health according to the Illinois EPA methodology (Illinois Administrative Code, Part 742: Tiered Approach to Corrective Action Objectives [TACO]) (Sharma and Reddy 2004). Since the site is located within a special designated area known as the Calumet area, an ecological risk assessment was performed based using a specifically developed ecotoxicity protocol by Calumet Ecotoxicology Roundtable Technical Team (CERTT 2007).

Table 6.1 summarizes the contaminants that exceed the threshold concentrations based on human and ecological risk. All other contaminant concentrations are below their respective acceptable levels. Contaminants in excess of threshold values include PAHs (specifically benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h) anthracene, indeno (1,2,3-cd) pyrene, and phenanthrene) and pesticides (specifically dieldrin, 4,4′-DDD, 4,4′-DDE, 4,4′-DDT), and several metals, including arsenic, barium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc. Contaminants identified in surface water are below the threshold levels and therefore do not require remediation.

Areas with PAHs, pesticides, and metals above actionable levels are depicted in Figure 6.2. The ratio of existing site contaminant concentration and the respective threshold contaminant concentration is plotted in

Table 6.1. Risk assessment

Contaminant	**Human risk (mg/kg)**	**Ecological risk (mg/kg)**	**Controlling scenario**	**Maximum concentration (mg/kg)**
Soil				
Benzo(a) anthracene	0.90	NA	Human risk	120
Benzo(a)pyrene	0.09	113	Human risk	110
Benzo(b) fluoranthene	0.90	10	Human risk	120
Benzo(k) fluoranthene	9.00	10	Human risk	61
Chrysene	88.0	NA	Human risk	100
Dibenzo(a,h) anthracene	0.09	NA	Human risk	21
Indeno(1,2,3-cd) pyrene	0.90	10	Human risk	54
Phenanthrene	NE	50	Ecological risk	170
Dieldrin	0.02	0.54	Human risk	0.04
4,4′-DDD	3.0	0.04	Ecological risk	0.17
4,4′-DDE	2.0	0.04	Ecological risk	0.6
4,4′-DDT	2.0	0.04	Ecological risk	0.35
Arsenic	13	31	Human risk	26
Barium	2,100	585	Ecological risk	850
Cadmium	78	3.37	Ecological risk	14.9
Chromium	230	131	Ecological risk	905
Copper	2,900	190	Ecological risk	257
Lead	400	430	Human risk	1,000
Mercury	10	1.3	Ecological risk	3.1

(*Continued*)

Table 6.1. Risk assessment (*Continued*)

Contaminant	**Human risk (mg/kg)**	**Ecological risk (mg/kg)**	**Controlling scenario**	**Maximum concentration (mg/kg)**
Nickel	1,600	210	Ecological risk	591
Selenium	2.4	1	Ecological risk	6.8
Silver	390	2	Ecological risk	8.46
Zinc	23,000	250	Ecological risk	603
Groundwater				
Lead	0.1	NA	Human risk	0.869
Selenium	0.05	NA	Human risk	0.057

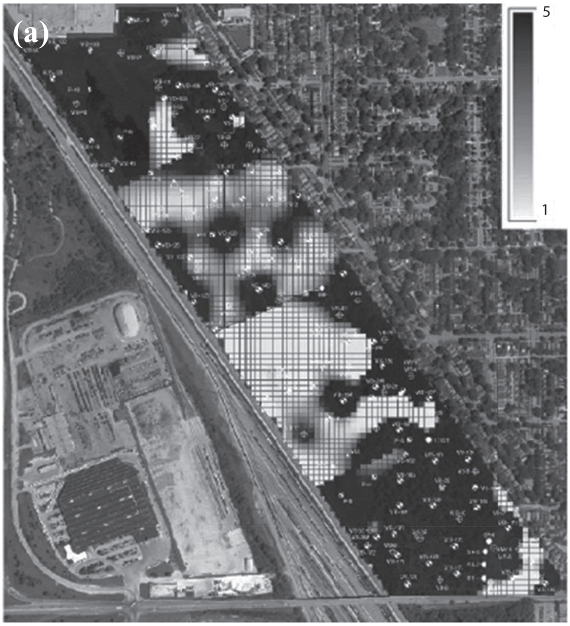


Figure 6.2. Map showing the areas where the contaminant concentrations exceeded the threshold levels based on (a) human and ecological risk for PAHs, (b) human and ecological risk for pesticides, and (c) human and ecological risk for metals.

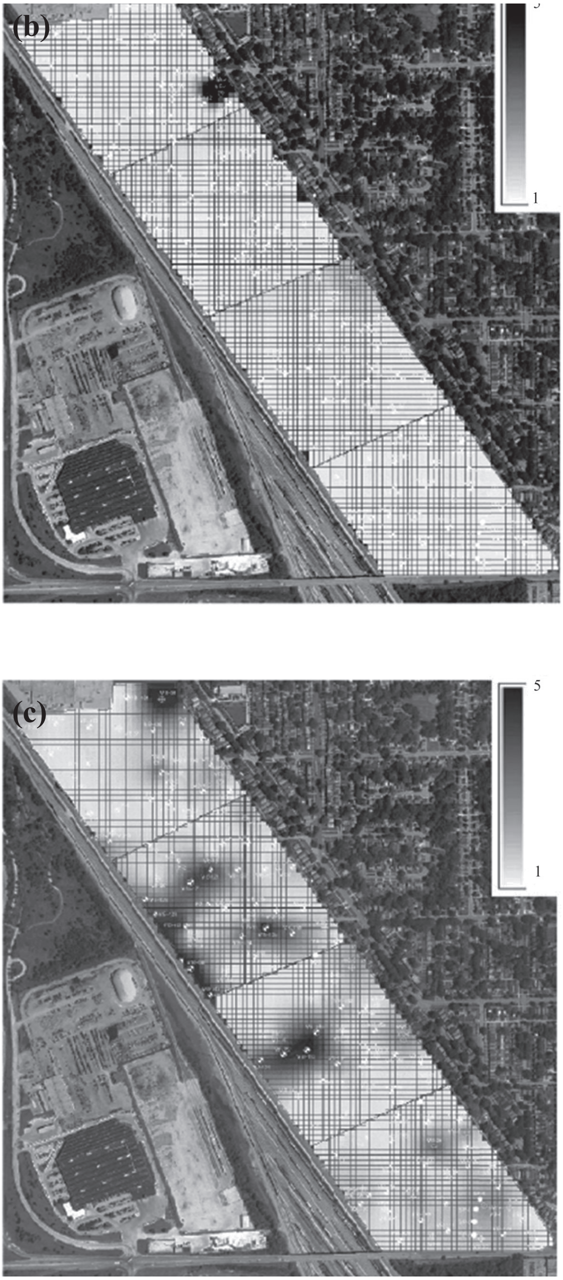


Figure 6.2. (*Continued*).

this figure. The scale ranges from one to five, the white color indicates the area where the ratio is less than or equal to one, and the black color indicates locations where the ratio is greater than one. The contaminants in some areas exceed five times the respective threshold contaminant levels. These results show that the risk posed by the presence of PAHs is higher as compared to pesticides and metals.

6.1.2 FRAMEWORK

Several potential soil and groundwater contamination remediation technologies have been considered for the site based on applicability, cost range, limitation, and commercial availability. For soils, excavation and disposal, phytoremediation, in situ chemical oxidation (ISCO), and solidification and stabilization have been identified as potential remediation alternatives. For groundwater, pump-and-treat, in situ flushing, permeable reactive barrier (PRB), and monitored natural attenuation (MNA) have been identified as potential remediation alternatives. A comparative assessment of potential remedial technologies was performed based on the best management practices (BMPs) as well as qualitative and quantitative assessments.

The general BMPs for the selected technologies have been assessed based on the BMPs listed in the Greener Cleanup Matrix developed by the Illinois EPA and the Toolkit for Greener Practices developed by the Minnesota Pollution Control Agency (ITRC 2011). In addition to BMPs, the green remediation evaluation matrix (GREM) tool was used to perform a qualitative comparison of remediation technologies for sustainability and adverse environmental impact. A quantitative assessment was also performed based on sustainability metrics. The sustainability metrics for the selected potential technologies were calculated using two tools: the Sustainable Remediation Tool (SRT) and SiteWise.

6.1.3 METRICS

Technologies with more BMPs were considered to be the better options. With respect to the GREM analysis, a score was given for each potential stressor (emissions, waste production, noise produced, etc.), ranging from 1 to 10 (1 assigned to the highest adverse impact, 10 assigned to the lowest adverse impact). An example GREM matrix for solidification and stabilization is shown in Table 6.2. Similar matrices were developed for each remediation technology. The remedial alternative with the highest total

Table 6.2. GREM for stabilization and solidification

Stressors	Affected media	Mechanism and effect	Y/N	Components	Score
Substance release and production					
Airborne NO_x and SO_x	Air	Acid rain and photochemical smog	Y	Equipment required to stabilize soil, hauling of material on site	1
Chloro-fluorocarbon vapors	Air	Ozone depletion	N	N/A	10
GHG emissions	Air	Atmospheric warming	Y	Equipment required to stabilize soil, hauling of material on site	1
Airborne particulates, toxic vapors, gases, water vapor	Air	General air pollution, toxic air, humidity increase	Y	Equipment required to stabilize soil, hauling of material on site	1
Liquid waste production	Water	Water toxicity, sediment toxicity, sediment	N	N/A	10
Solid waste production	Land	Land use, toxicity	Y	On-site construction debris	8
Thermal releases					
Warm water	Water	Habitat warming	N	N/A	10
Warm vapor	Air	Atmospheric humidity	N	N/A	10

(*Continued*)

Table 6.2. GREM for stabilization and solidification (*Continued*)

Stressors	**Affected media**	**Mechanism and effect**	**Y/N**	**Components**	**Score**
Physical disturbances and disruptions					
Soil structure disruption	Land	Habitat destruction, soil infertility	Y	Stabilization of soil	1
Noise, odor, vibration, aesthetics	General environment	Nuisance and safety	Y	Noise from machinery and truck hauling to site	3
Traffic	Land; general environment	Nuisance and safety	Y	Work crews to the site, removal of construction debris and hauling of solidification materials	5
Land stagnation	Land; general environment	Remediation time, cleanup efficiency, redevelopment	Y	Lost use during remediation	8
Resource depletion and gain (recycling)					
Petroleum (energy)	Subsurface	Consumption	Y	Hauling of stabilization material, equipment	4
Mineral	Subsurface	Consumption	N	N/A	10
Construction materials (soil, concrete, plastic)	Land	Consumption and reuse	Y	Construction supplies, solidification materials	5
Land and space	Land	Impoundment and reuse	N	N/A	10
Surface water and groundwater	Water, land (subsidence)	Impoundment, sequester and reuse	Y	Water used for solidification	7
Biology resources (plants, trees, animals, microorganisms)	Air, water, land and forest, subsurface	Species disappearance, diversity reduction, regenerative ability reduction	Y	Construction activities on entire site	3

score was considered the greenest remedial alternative in terms of least adverse environmental impacts.

For the two quantitative methods, the analysis results include greenhouse gas (GHG) emissions, oxides of nitrogen emission, oxides of sulfur emission, small particulate matter emission, total energy used, accident risk injury and fatality, and cost. SRT is only applicable to specific technologies; therefore, it was used to assess the excavation and disposal option for soils as well as pump-and-treat, PRB, and MNA for groundwater in this study. The SiteWise tool can be used for any remedial technology provided all activities involved in the remediation implementation have been identified. This tool was used for all selected potential remediation alternatives under consideration.

6.1.4 ASSESSMENT AND OUTCOME

Based on the BMP comparison considering excavation, disposal, and pump-and-treat, all remediation technologies can incorporate many BMPs (Table 6.3). The GREM scores for selected potential technologies are compared in Figure 6.3. The figure shows the respective scores for each remediation method. According to the GREM analysis, phytoremediation is best suited for soil remediation, while MNA is best suited for groundwater remediation.

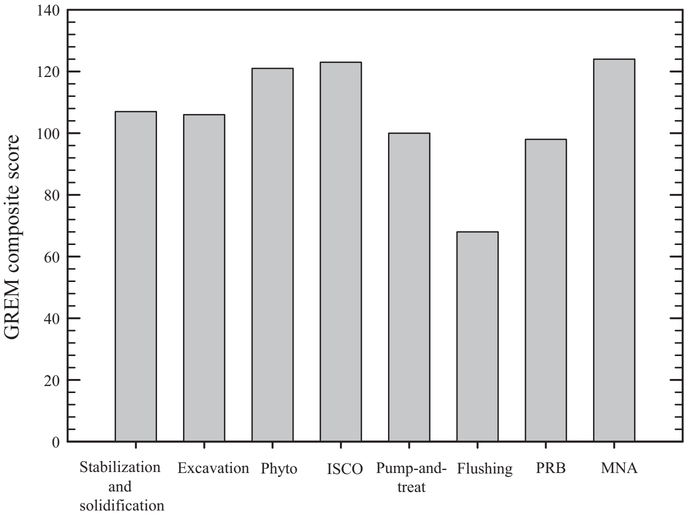


Figure 6.3. GREM analysis for soil and groundwater remediation technologies.

Table 6.3. Comparison of BMPs for different remedial options

Method	**Greener cleanups matrix**	**Toolkit for greener practices**	**Total**
Soil			
Solidification and stabilization	✓(Energy efficient) ✓(Passive in situ)	✓(In situ) ✓(Possibility for recycling unused material)	✓✓✓✓
Phytoremediation	✓(Reduced excavation requirements) ✓(Passive in situ)	✓(In situ) ✓(No pumping required, i.e., efficient and innovative)	✓✓✓✓
Excavation and disposal	None	None	None
Chemical oxidation	✓(Reduced excavation requirements) ✓(Passive in situ)	✓(In situ) ✓(No pumping required, i.e., efficient and innovative)	✓✓✓✓
Groundwater			
PRB	✓(Use of permeable barriers) ✓(Energy efficient) ✓(Passive in situ)	✓(In situ) ✓(No pumping required, i.e., efficient and innovative)	✓✓✓✓
In situ flushing	✓(In situ) ✓(Recycling of water)	✓(In situ) ✓(Assuming that we can recycle water)	✓✓✓✓
MNA	✓(In situ) ✓(Reduced excavation requirements)	✓(In situ) ✓(No pumping required, i.e., efficient and innovative)	✓✓✓✓
Pump-and-treat	None	None	None

SRT and SiteWise results are shown in Figures 6.4 and 6.5, respectively. Tables 6.4 through 6.6 show the relative impacts of soil and groundwater remediation technologies according to SiteWise analysis. Solidification and stabilization was selected for soil zones where metal concentrations were very high, and phytoremediation was selected for the remaining areas of impact. Since the groundwater was encountered at a shallow depth and contaminant concentrations were low, MNA integrated with phytoremediation was selected as the best groundwater remediation alternative.

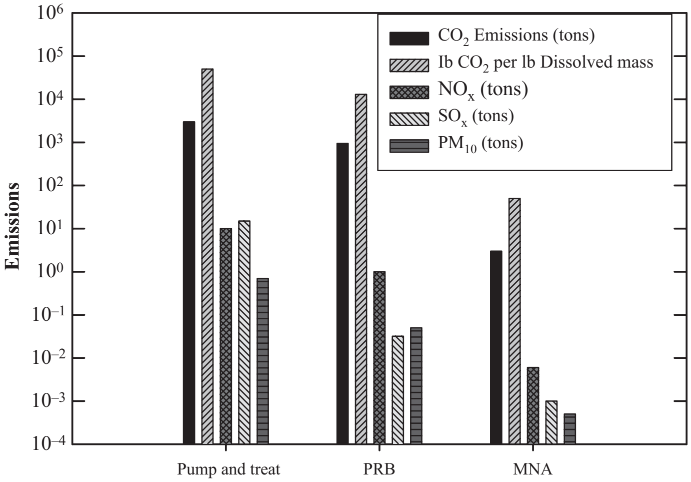


Figure 6.4. Typical SRT™ results: emission comparison for groundwater remediation technologies.

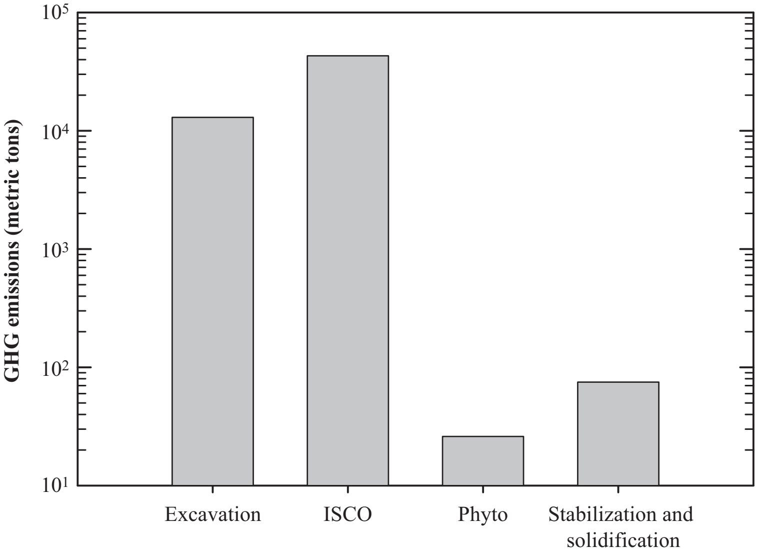


Figure 6.5. Typical SiteWise™ results: GHG emission comparison for soil remediation technologies.

Table 6.4. Relative impacts of soil remediation technologies based on SiteWise

Remedial alternatives	GHG emissions	Energy usage	Water usage	NO_x emissions	SO_x emissions	PM_{10} emissions	Accident risk fatality	Accident risk injury
Excavation	Low	Low	High	High	High	High	High	High
ISCO	High	High	Low	Low	Low	Low	Low	Low
Phytoremediation	Low	Low	Low	Low	Low	Low	Low	Low
Stabilization and solidification	Low	Low	High	Low	Low	Low	Medium	Medium

Table 6.5. Relative impacts of groundwater remediation technologies based on SiteWise

Remedial alternatives	GHG emissions	Energy usage	Water usage	NO_x emissions	SO_x emissions	PM_{10} emissions	Accident risk fatality	Accident risk injury
MNA	Low	Low	Low	Low	Low	Low	Medium	Low
PRB	Low	Low	Low	Low	Low	Low	High	Medium
Pump-and-treat	High	High	Low	Low	Low	Low	High	Medium
Soil flushing	Low	Low	High	High	High	High	High	High

Table 6.6. Summary of SiteWise comparison of sustainability metrics between phytoremediation with enhanced biostimulation (Phyto-EB) and excavation at Area C

Remedial alternatives	GHG emissions	Energy usage	Water usage	NO_x emissions	SO_x emissions	PM_{10} emissions	Accident risk fatality	Accident risk injury
Phyto-EB	Medium	Medium	High	Medium	Low	Low	High	High
Excavate	High	High	Low	High	High	High	High	Medium

6.1.5 REMEDIATION ALTERNATIVE SELECTION

Phytoremediation has been selected to treat the majority of the site, and solidification and stabilization has been selected for selected areas exhibiting relatively high metal concentrations. Solidification and stabilization is proposed for implementation in approximately 7.5 acres of the site, and phytoremediation is proposed for 95 acres of the site. Considering the different remedial options, solidification and stabilization was initially identified as a feasible alternative for areas on the site where multiple types of contamination exist. Further assessment determined that while solidification and stabilization is highly effective for contaminants on the site, it is also expensive. Therefore, solidification and stabilization was determined to be best applied in areas with high contaminant concentrations that pose a threat of groundwater contamination. A cement-based solidification and stabilization mix design has been proposed to treat these impacted soils and minimize the potential for groundwater impact.

Phytoremediation involves the removal, stabilization, or degradation of contaminants in soils by plants (ITRC 2009). The majority of plant installation would consist of grasses with trees at specific locations to address existing groundwater impacts. Sunflower plantings may be used in appropriate locations to address lead, arsenic, and silver, and cattails may be planted in areas to address lead and zinc. Rye grass and tall fescue may be used in appropriate locations for the degradation of PAHs at identified areas. Hybrid poplars may be used in the extreme northeast corner of the site where larger and deeper contamination of heavy metals have been identified as well as in locations where groundwater contamination has been identified.

Groundwater contamination is not as great a concern at the site as soil contamination; further, there is no complete groundwater exposure pathway at the site. A combination of MNA and phytoremediation is recommended to address groundwater remediation.

Periodic groundwater monitoring is recommended to study the cumulative effect of the recommended phytoremediation and MNA alternatives. Phytoremediation monitoring will also be performed through testing of the leaves and cuttings of the plants.

6.1.6 CONCLUSIONS

As a result of past illegal dumping activities, soils and groundwater at a large vacant and wooded marshland site (117 acres) have been contaminated with heavy metals, PAHs, and pesticides. Conversion of the site into an ecological open space reserve has been proposed. Some of the contaminants, particularly PAHs and heavy metals, have been identified at levels that pose a risk to human health and ecology; therefore, remediation action is warranted. Following qualitative and quantitative assessments, remediation alternatives have been recommended to address contaminated soil and groundwater. The assessments described earlier considered sustainability-related metrics to assess potential impacts on the environment. A combination of remediation methods were identified as the best alternatives for the site. Solidification and stabilization (to be applied in areas of high contaminant concentrations) and phytoremediation (to be applied in other contaminated areas) have been recommended for the remediation of soils with PAHs and heavy metals, while MNA and phytoremediation have been recommended for the treatment of impacted groundwater.

6.2 CASE STUDY 2: INDIAN RIDGE MARSH SITE

6.2.1 PROJECT BACKGROUND

Recent efforts by the City of Chicago and the Illinois Department of Natural Resources to restore historically industrialized wetlands and prairies in the Calumet region (southeast Chicago) have prompted the evaluation of potential remedial options for several tracts of land slated for redevelopment as part of the Great Lakes Restoration Initiative (GLRI), a multiagency effort to increase funding for remediation and protection of the Great Lakes ecosystems. The Indian Ridge Marsh (IRM) has significant and widespread historic contamination, including documented impacts to soil, sediments, surface water, and groundwater. The restoration of wetland and prairie habitats at IRM holds significant ecological value, especially for several endangered birds (e.g., black crowned night heron) that nest seasonally in these areas (Kamins et al. 2002). Multiple contaminant classes are present on-site, heavy metals, pesticides, VOCs, PAHs, pesticides, and one observed instance of a light nonaqueous phase liquid (LNAPL) plume containing petroleum hydrocarbons.

The contaminated areas that posed the greatest risk to human and ecological health were identified through the comparison of measured sample concentrations to risk-based screening levels (RBSLs), TACO, and the Calumet Area Ecotoxicological Protocol (CAEP). Six areas of concern (AOCs), identified as Areas A, B, C, D, E, and F, were established based on the geographic distribution of samples with contaminant levels exceeding established RBSLs (Figure 6.6). The AOCs were targeted for direct remediation, and data regarding contaminant distribution in the

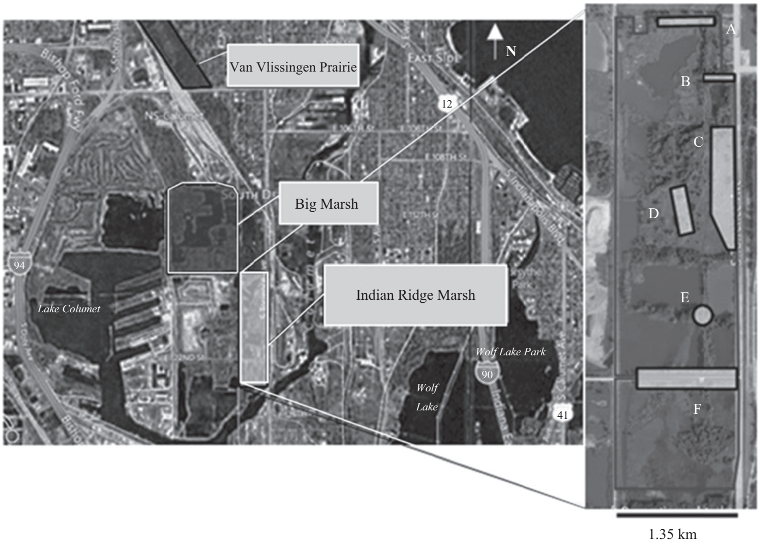


Figure 6.6. Area map showing three wetlands slated for restoration as part of the Millennium Reserve, proposed as part of the GLRI. Inset map shows AOCs identified at IRM.

subsurface, depth to the water table, and area of impacted media from each AOC were used to estimate overall energy use and emissions associated with the remediation of these areas.

Previous assessments identified the presence of VOCs, semivolatile organic compounds (SVOCs), pesticides, and heavy metals distributed throughout the soil, sediment, groundwater, and surface waters resulting from on-site and off-site activities, including historic legal and illegal dumping of waste and slag. Sources of off-site contamination include the Lake Calumet Cluster sites (LCCS), located directly adjacent and topographically upgradient from IRM to the west, which is believed to have a direct impact on the IRM sediments and surface waters through discharge of overland flow from LCCS. The LCCS, formerly used for both regulated and unregulated industrial facilities and waste disposal, was placed on the National Priorities List (NPL) in 2010. LCCS is currently undergoing remedial actions that will impact potential future contaminant transport into IRM.

6.2.2 FRAMEWORK

Qualitative and quantitative analyses were conducted to evaluate potential environmental impacts associated with each remedial option using green and sustainable remediation (GSR) tools such as the GREM, SiteWise, and the SRT. Following a qualitative evaluation of sustainability metrics using GREM (i.e., noise, worker safety, and aesthetics), a quantitative evaluation of energy and resource consumption was conducted using both SRT and SiteWise considering several project phases, including the remedial investigation, remedial action construction, operations and maintenance, and long-term monitoring. Additionally, the Social Sustainability Evaluation Matrix (SSEM) tool was applied to the IRM project to evaluate the social impacts of both remedial alternatives.

6.2.3 METRICS

Estimates of material and labor needs, treatment time, volume of affected soil or groundwater to be treated (based on the surface area and depth of contamination in each AOC), and assumptions specific to certain treatments were made for each remedial alternative and input into SiteWise and SRT. Output from these models included estimates of project energy and water consumption, GHG emissions (CO_2, N_2O, NO_X, SO_X), and accident and injury risk to workers. The SiteWise and SRT user manuals present specific equations and conversion factors employed by the software to generate the reported estimates (AFCEE 2010; Bhargava and Sirabian 2011).

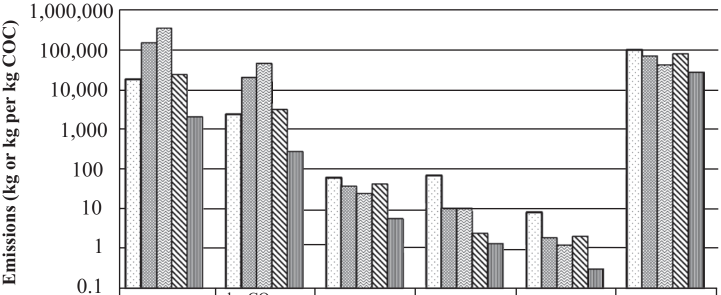
6.2.4 ASSESSMENT AND OUTCOME

Several treatment types were deemed inappropriate for the site conditions and contaminant chemistries and were excluded from extensive sustainability assessments. Several site-specific considerations narrowed the range of feasible remedies, including the following:

- The shallow water table (3 to 15 feet below the ground surface), the presence of numerous surface ponds, and extensive wetlands limited the use of technologies that were restricted for use in the vadose zone or those that required extensive dewatering of the soils.
- The widespread distribution of shallow subsurface contamination poses logistical difficulties for treating or removing large volumes of soil. In situ remediation alternatives are preferable to ex situ technologies.
- The presence of mixed contaminant types (heavy metals, PAHs, VOCs, SVOCs) requires a remediation alternative that can be applied to a variety of chemical compounds.

- The heterogeneous nature and low hydraulic conductivity of the surficial sediments (fill material, silty sands interbedded with clay lenses; hydraulic conductivity = 10^{-5} to 10^{-3} cm/s) limit the effectiveness of technologies that require pumping large amounts of liquids through contaminated sediments or rely on high groundwater flow rates.
- A proposed future open space land use necessitates habitat and ecological restoration goals; therefore, remediation should minimize the degree of permanent or irreversible site disturbance.

Figure 6.7 shows an example of output provided by the SRT tool, comparing air pollutant emissions for groundwater remediation alternatives considered for Area F—pump-and-treat, enhanced bioremediation, ISCO, PRB, and MNA. Because SRT does not include phytoremediation as a remedial alternative, results from SRT only provide comparisons among active remedies that can be employed if treatment time is a constraint. Since the end use of the site involves habitat restoration and preservation, overall project cost and environmental impact remain more important factors than treatment time. As a result, a passive, in situ remediation alternative with minimal site disturbance (e.g., phytoremediation) is ideal. These initial estimates, coupled with the continued use of Site-Wise during remedy implementation, allows for detailed accounting of



	kg CO_2	kg CO_2 per kg COC	kg NO_x	kg SO_x	kg PM_{10}	MJ
	CO_2 emissions		Criteria air pollutant emissions			Total energy consumed
□Pump-and-treat	18,000	2,404	61	69	8.1	100,000
▩Enhanced bio.	150,000	19,958	36	10	1.8	69,000
▦ISCO	350,000	45,359	24	10	1.2	42,000
▧PRB	24,000	3,175	41	2.4	2	79,000
▥LTA/MNA	2,100	281	5.6	1.3	0.3	27,000

Figure 6.7. Select output from SRT analyses among active remedial alternatives for groundwater treatment at Area F. The table and graph show the estimated emissions of CO_2 and other criteria air pollutants (NO_x, SO_x, PM_{10}).

the environmental impacts of the project without excessive (and costly) sampling and analyses of affected media and emissions.

Ideally, all AOCs will be remediated; however, treatment of the entire contaminated area may be cost-prohibitive. Modeling estimates are applied initially to Areas C and F, which have the highest contaminant concentrations and most complex contaminant mixtures; these areas have been identified as priority areas for active remediation. The remaining areas (A, B, D, and E) may be monitored for natural attenuation of onsite contaminants.

A remedial strategy was chosen from the results of both quantitative and qualitative sustainability assessments. The criteria for selecting applicable remedial technologies are based on site-specific conditions, including geologic setting, local hydrology and hydrogeology, the nature of topsoil and surficial sediments (low permeability clay-rich glacial till and silty sands; heterogeneous distribution of fill materials), the nature and distribution of identified contaminants, and the end-use of the site.

The SSEM tool was applied to two soil remediation alternatives—excavation and phytoremediation with enhanced bioremediation (phyto-EB). Some reasonable justifications for the assigned scores in SSEM for the evaluation of metrics are as follows:

- With respect to the socioindividual dimension, the phyto-EB option was assumed to create a positive impact on quality-of-life issues since it involves the least disturbance of contaminated soil, limiting dust generation, and reduced generated traffic. The phyto-EB option can enhance the aesthetics of the community and provide opportunities for the recreation and development of new skills as compared to the excavation and disposal option. Phyto-EB results in less site disturbance, enhances aesthetics, and may offer an attractive destination as compared to a site where excavation has resulted in a less aesthetically pleasing alteration of the land.
- Under the socioinstitutional dimension, phyto-EB was assumed to create positive impacts by fostering future land use for community-based recreational purposes and improved impacts resulting from the enhancement of architecture and aesthetics of surrounding communities. Phyto-EB could generate positive participation from government, community and volunteer organizations, and local networks. Excavation and disposal often results in a higher degree of negative responses from local and community organizations due to the potential health hazards during remediation.
- Under the socioeconomic dimension, excavation and disposal resulted in the highest positive impact due to job generation and

employment potential, both directly (employment directly associated with the remedial activity) and indirectly (enhanced economic activity in the community due to patronage of local businesses). Both impacts result in increased economic development of the surrounding community.

Under the socioenvironmental dimension, phyto-EB has higher positive impacts due to a higher degree of protection to workers during remediation and postremediation activity. Phyto-EB is an in situ technology that avoids future impacts from emissions and roadway wear generated by large trucking loads during excavation and disposal; phyto-EB exhibits a greater degree of *greenness*. However, the downside is that the plants require a minimum of five growing seasons to effectively remediate the contaminant levels, while excavation and disposal is a much quicker alternative.

Results of the social sustainability assessment are shown in Figure 6.8. Overall, SSEM results indicate that the phyto-EB remedial option has the highest positive impact on the surrounding community as compared to the excavation and disposal option. It is also evident that if no remedial action were taken, there would be a negative impact on the surrounding community and is considered to be the worst-case scenario.

6.2.5 REMEDIATION ALTERNATIVE SELECTION

The recommended strategy for remediation of IRM consists of the phyto-EB option. This alternative will act to stimulate existing soil

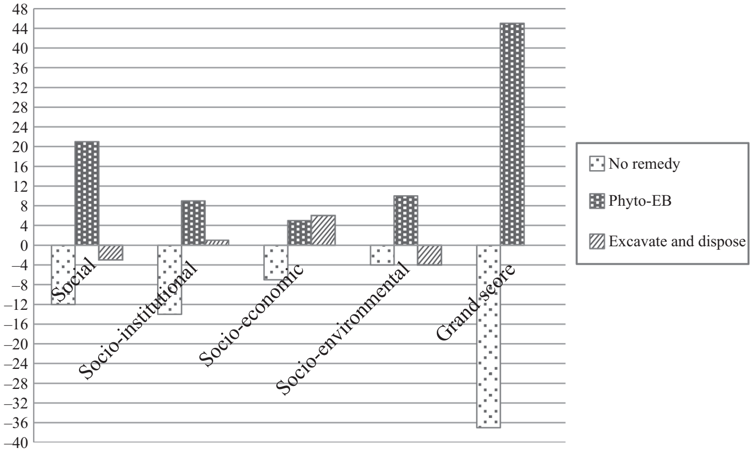


Figure 6.8. *SSEM* results for IRM site.

microorganisms to enhance the degradation of organic contaminants at all identified AOCs. Native tree species with high growth and transpiration rates, deep rooting depths, and the ability to accumulate and sequester contaminants of concern will be employed. Trees will be planted in stands and spaced approximately 10 feet apart to achieve maximum growth density and remedial efficiency. In areas with both groundwater and soil contamination (B, C, E, and F), approximately 50 percent of the trees will be placed in lined trenches to encourage root growth toward the contaminated aquifer. The liners will be modeled after the proprietary ANS TTTS® TreeWell system used successfully at Argonne National Laboratory with the same tree species (willows, cottonwoods, and poplars). This technique also allows for greater tree densities in the stands, as root systems will not grow as wide, reducing the lateral extent of each tree in the root zone.

All treated areas will receive soil amendments in the form of organic compost and an initial application of balanced NPK (10-10-10) fertilizer to stimulate new root growth. Oxygen reactive compounds (ORCs) will be mixed into tilled soils during planting. This form of oxygen additive is preferred over direct oxygen injection because it is less energy-intensive, less costly, does not require the installation of injection wells, and releases oxygen in the soil over time rather than in pulses, improving the long-term performance of the plants. One drawback of ORCs is the potential to raise the local soil pH, which will be counteracted by the addition of acidifying soil amendments (e.g., granular S, gypsum or $Al_2(SO_4)_3$, leaf litter) (Rentz et al. 2003). The addition of oxygen to the soil is intended to stimulate microbial activity in the rhizosphere, enhancing rhizodegradation processes associated with the plants as well as microbial degradation processes that occur in natural soils when sufficient nutrients and oxygen are available (Rentz et al. 2003). Regular applications (two to three times per growing season) of organic compost will provide ample nutrients for biostimulation processes and maintain overall soil quality and pH.

A vegetative cover of grasses (*Lotus corniculatus*) and legumes (*Lolium perenne* and *Phalaris arundinacea*) will be put in place in between treated areas to help stabilize soils, maximize total water use, minimize erosion, and keep shallow soils dry to promote deeper rooting depths of the phreatophytic trees (ITRC 2009; U.S. EPA 2003). The vegetative cover also serves to reduce the flow of contaminated surface waters to the nearby Calumet River or other offsite waterways by increasing infiltration into shallow soils. This will also serve to minimize the production of leachate as precipitation flows through contaminated soils and groundwater. Additionally, the grasses and legumes will help remediate contaminants in shallow subsurface soils that have less contact with the deeper root systems of the willows, poplars, and cottonwoods.

To minimize cross-contamination of surface waters with contaminated sediments and soils, a riparian buffer zone (5 to 10 feet in width) will be installed around surface water reservoirs in close proximity to AOCs. The riparian buffer will slow water transport between surface and groundwater, limiting erosion of surficial sediments and helping to contain existing contamination within the site boundaries. The buffer zone will consist of cattails, small duckweed, and common reed already present onsite; additional plants will be added in areas that lack sufficient native vegetation to serve this purpose.

The remedial progress of each AOC will need to be evaluated after every five years, the approximate length of one growth cycle for the selected trees. This cycle refers to the four to six years that the trees require to grow from saplings to mature trees, at which point growth rates and phytoremediation efficiency decrease. At the end of each cycle, mature trees will be replaced in order for new saplings to be planted. It is projected that a minimum of three growing cycles (up to 15 years) will be required to reduce the contamination levels to an acceptable amount (ITRC 2009). Areas with higher contaminant concentrations (i.e., Areas C and F) will require more growth cycles than areas that have lower levels of contamination, which may be remediated within the first growth cycle. The number of cycles needed at each AOC will be determined as remedial progress is monitored and overall uptake and degradation rates can be quantified at the site.

Another major source of GHG emissions in phytoremediation is tilling of the land prior to planting tree stands. The use of ORCs can reduce the depth and frequency of tilling required for sufficient soil aeration, though some tilling will be required initially to incorporate the ORCs with the soil. Proper management of the phytoremediation application will require regular monitoring of plant health to assess the need for additional soil amendments. This will ensure that only the necessary amount of fertilizer is applied to ensure ready plant growth.

6.2.6 CONCLUSIONS

Based on the site conditions and history of widespread, low-level contamination on- and off-site, a passive remedial strategy with minimal site disturbance is recommended. Due to the mixed contaminant chemistries present, shallow water table and heterogeneous subsurface hydrology, other remedial technologies were disqualified as appropriate treatments for all contaminants of concern at IRM. In terms of compatibility with future site use and sustainability metrics, phytoremediation coupled with enhanced bioremediation is the ideal technology for the remediation of IRM. This technology is in line with future site use goals as part of the Calumet Open Space Reserve (COSR) that includes the preservation of wetland habitats; improvement of existing habitat, which will be addressed as overall soil quality and vegetative health is improved over the course of treatment; and creation of new habitats, which can be incorporated into planting schemes after high levels of contamination are reduced in the early cycles of tree growth and replacement. It is recommended that an initial survey of existing vegetation on-site be conducted to determine applicability to phytoremediation processes. Further sampling of affected media in under-represented areas will be necessary to better constrain the spatial extent of areas of high-level contamination. This will allow the proposed design to be tailored to current conditions and optimized to utilize existing vegetation with minimal site disturbance. Further benefits from this remedial alternative extend from educational and public outreach opportunities that can be incorporated into the remediation and habitat rehabilitation process. Information on native vegetation and wildlife at IRM can be disseminated throughout community bulletins and through posted signs onsite that inform the public of ongoing remedial activities and what steps are being taken to ensure that sensitive habitats are being protected. This will improve public acceptance of the remedial activities at IRM and garner support for habitat restoration goals and improvement of degraded sites and wetlands throughout the Calumet region.

6.3 CASE STUDY 3: FORMER MATTHIESSEN AND HEGELER ZINC FACILITY

6.3.1 PROJECT BACKGROUND

The Matthiessen and Hegeler Zinc facility, located in LaSalle, Illinois, was originally used for zinc smelting operations, which began in 1907. In addition to zinc smelting, the site was mined for coal; and zinc sheet and sulfuric acid were produced and cadmium was processed. In 1954, Hegeler dissolved and the site was then used for filling containers with insecticides, shaving products, and other materials by Peterson Filing and Packaging. In 1956, the Illinois Fireworks Company purchased the remainder of the land from National Distillers, the sole stockholder of the land, for the purpose of manufacturing fireworks. A recent part-owner, Millennium Petrochemicals (formerly known as National Distillers), filed for bankruptcy in 2009. Geographically, the approximately 100-acre site is located west of the village of Hegeler. The area is rural and bordered by farmland. A residential community is located less than 0.25 miles to the east of the site. Another residential area is located approximately 0.5 miles to the northeast in Tilton, Illinois. The site is directly bordered by agricultural land on the north, west, and south. Four separate impoundments are located on the site. Additionally, a large slag pile occupies 5.9 acres on the western portion of the site. The pile reaches 53 feet above grade. The slag is a result of smelting operations and contains unburned residues and metals such as lead, arsenic, cadmium, and zinc, as well as wood, brick, and concrete debris from buildings that were previously on-site.

The surface geology of Vermilion County is composed mainly of Wisconsin-aged glacial drift deposits, which consist of clay-rich till, with some deposits of sand and gravel. The uppermost layer consists of a fill with a typical thickness between one to three feet. The fill is composed mainly of slag. The first aquifer in the region is shallow and unconfined, between one and six feet. The surficial hydrogeology at the site consists of a silty, sandy, and gravely clay till.

The Illinois EPA and Weston Solutions collected on-site soil, slag, sediment, and groundwater samples during investigations conducted between 2000 and 2006. Samples were taken on-site as well as the neighboring residential area. Residential soil sample tests found that lead, arsenic, and copper concentrations were greater than levels established within Illinois EPA TACO regulations for protection of residential exposure. Residential soils were above regulatory limits; however, the concentrations were not as high as the on-site soils. Soil and waste samples collected on-site were compared to TACO regulatory limits for industrial and commercial properties. This analysis strictly focused on remediating the site soils. The majority of screening level exceedances were due to elevated arsenic, cadmium, lead, and zinc concentrations, with the highest metal concentrations in the north-central portions of the site as well as within the slag pile. The general extent of metals contamination in site soils extends to the site's boundaries. PAHs were detected in site soils above screening levels. The areas of PAH contamination appear to coincide with areas of elevated metals, which are the main contaminants and are associated with the slag. The underlying clay soil exhibited significantly lower concentrations of metals, indicating that the majority of the elevated metal concentrations are concentrated within the fill material.

To prevent trespassers from coming into contact with the contaminated soil and waste material, the Illinois EPA installed a six-foot-high chain link fence around the site. In 2005, the site was officially added to the NPL due to the risk potential of human contact with the site contamination levels.

6.3.2 FRAMEWORK

The focus of this study and analysis is specifically contaminated on-site soils. It is assumed that the slag pile, surface water, and contaminated groundwater will be treated separately. A significant challenge with remediating the site is its large contaminated surface area. SimaPro software has been used to evaluate the life-cycle impact of two common methods of treatment for environmental impact: landfilling (excavation and hauling) and in situ treatment by solidification and stabilization.

The SimaPro software was used to assess the life cycle of the remediation alternatives for environmental impacts. While this may include all portions of the life cycle, from raw material extraction through material processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling, a more limited approach was used. The system boundary is discussed in the next section.

Beyond human health and environmental impacts, economic and social impacts also contribute to the decision to use one method over another. From a social perspective, it is important to consider the nearby communities and the impact attributed to disruptive truck traffic and the resulting emissions. The SSEM tool described in the previous case study has also been applied here to assess socioinstitutional, socioeconomic, and socioenvironmental factors.

6.3.3 METRICS

Prior to performing a life-cycle assessment (LCA) on the two treatment methods, it is important to set the system boundaries. For instance, while excavation and hauling requires the use of excavators and haul trucks, this analysis will not trace all of the inputs and outputs associated with producing the equipment needed to perform the construction. This analysis will not include mobilization and demobilization of equipment to the site. Additionally, it will not include impacts associated with constructing the landfill that the contaminated waste would be disposed in. This analysis will trace the following inputs and outputs.

Excavation and Hauling

- Impacts associated with excavating the contaminated soil
- Impacts associated with hauling the contaminated soil to the nearest landfill
- Impacts associated with extracting and backfilling clean soil fill

Solidification and Stabilization

- Impacts associated with manufacturing and transporting Portland cement
- Impacts associated with water use for solidification and stabilization
- Impacts associated with mixing the Portland cement mix into the contaminated soil
- Impacts associated with transporting and installing topsoil for vegetation

A summary of the estimated quantities are presented in Table 6.7. A constant impact depth of two feet of contaminated soil is assumed throughout the 100-acre site. The cement application rate is site-specific as well. Cement is an integral component of this analysis. Typical ranges can be between 10 and 40 percent. For this analysis, a 40 percent cement application rate was used. The nearest hazardous waste landfill is in Peoria, Illinois, which is approximately 65 miles from the project site. Two separate line items were included in the analysis for soil transportation. The first line item is for hauling the soil from the project site to the landfill, the second line item is for transporting the empty trucks back to the project site. Because the mass of the truck will differ significantly when it is empty and full, two different line items are appropriate. This also applies to transporting the clean sand fill as well as cement. The clean fill and cement are both available in the nearby town of Danville, Illinois, which is approximately 5¼ miles from the site. To support vegetation growth, it was assumed that one foot of clean fill over the site would be appropriate for the solidification and stabilization treatment. A total of two feet of fill is assumed for the excavation and haul method to make up for the excavated soil.

Clearly the largest energy use is attributed to transporting excavated contaminated soil to the landfill, and transporting the empty trucks back to the project site. The distance to and from the landfill plays a critical role in the LCA for excavation and hauling. In the following section, a separate analysis will be performed assuming the landfill is on-site.

Various databases are available for use in a LCA. For this study, the Building for Environmental and Economic Sustainability (BEES) database

Table 6.7. Input materials and processes for SimaPro analysis

Material and process	Excavation and hauling	Stabilization and solidification
Excavate contaminated soil	327,000 yd^3	NA
Transport soil to landfill	54,867,180 ton-mile	NA
Transport trucks back to site	36,212,340 ton-mile	NA
Mine clean fill for cover soil	359,200 tons	179,600 tons
Transport fill from supplier	3,696,140 ton-mile	1,795,270 ton-mile
Install clean fill	327,000 yd^3	163,500 yd^3
Transport trucks back to supplier	2,904,110 ton-mile	1,411,370 ton-mile
Cement for stabilization and solidification (40%)	NA	196,800 tons
Water for stabilization and solidification	NA	78,740 tons
Transport cement and water to site	NA	1,631,530 ton-mile
Mix cement and water into soil	NA	523,180 yd^3
Transport cement trucks back	NA	964,090 ton-mile

was utilized. BEES combines a partial LCA and life-cycle cost for building and construction materials. The BEES database characterizes the stressors that potentially contribute to ozone depletion, global warming, smog formation, ecotoxicity, human health effects, fossil fuel depletion, natural resource depletion, habitat alteration, water intake, and indoor air quality.

6.3.4 ASSESSMENT AND OUTCOME

Using the values in Table 6.7 for each remediation method, a LCA was modeled to compare each method. The results of this analysis can be found in Figure 6.9. Excavation and hauling results in greater impacts in every category except human health (cancer) when compared to solidification and stabilization. A separate analysis for each remediation method distributes the impacts associated with each process.

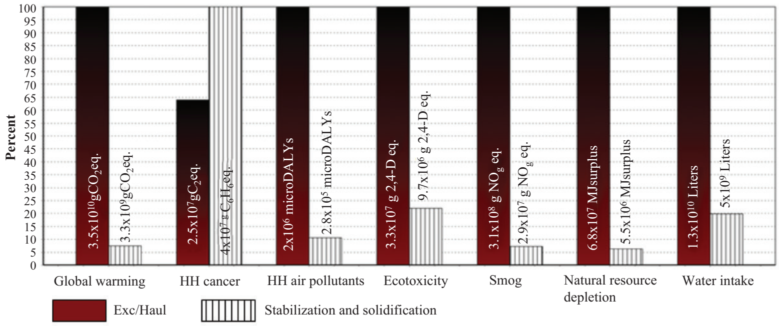


Figure 6.9. LCA comparing excavation and hauling to solidification and stabilization.

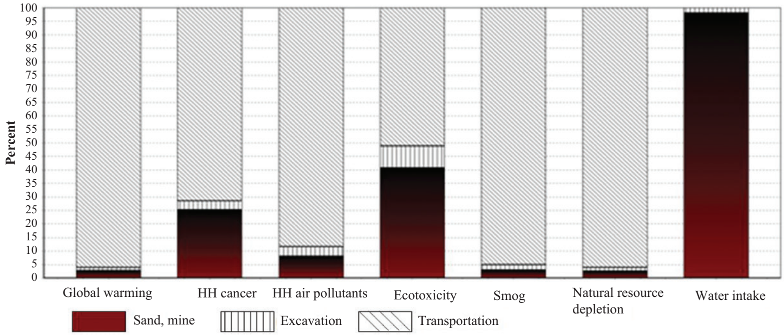


Figure 6.10. LCA for excavation and hauling.

Figure 6.10 illustrates the associated impacts of excavation and hauling. The largest contributor for water intake is sand mining, whereas the large amount of transportation contributed most to every other category.

Figure 6.11 illustrates the impacts associated with solidification and stabilization. The largest contributor to water intake is sand mining. The largest contributor to human health is the manufacturing of cement. Transportation is the largest contributor to global warming, smog formation, and natural resource depletion. The manufacturing of cement is the largest contributor to stressors that cause cancer. This is due to the energy-intensive process of manufacturing cement. A variety of pollutants are emitted from the burning of fuels and heating of raw materials, among other processes, used to make cement. These include mercury, acidic gases, and particulate matter (EPA).

The largest impact associated with the excavation and haul remediation alternative is transportation. Reuse of impacted soil on-site would

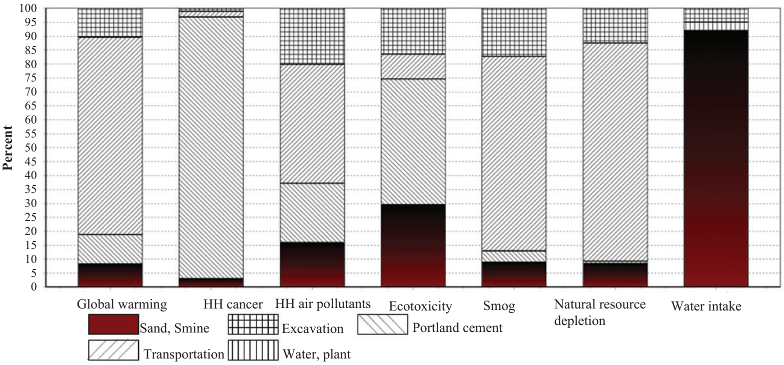


Figure 6.11. LCA for solidification and stabilization.

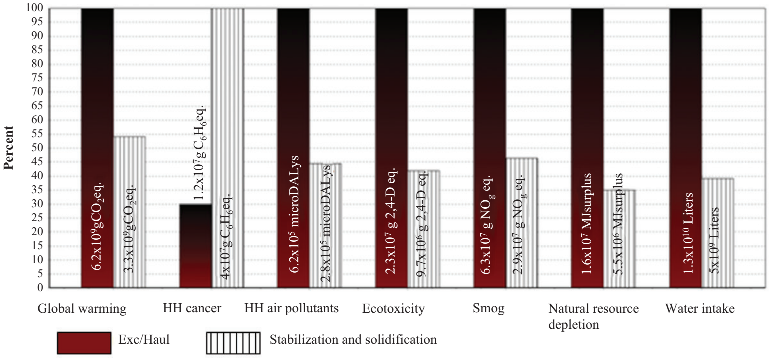


Figure 6.12. LCA comparing excavation and hauling and stabilization and solidification with onsite landfill.

result in significant impact reductions, as shown in Figure 6.12. Even when eliminating the return trip of empty trucks to the site from the analysis, the excavation and haul option would still result in greater impacts than solidification and stabilization, although the differences would be less drastic. While solidification and stabilization contributed only 10 percent to global warming as compared to excavation and haul (Figure 6.13), the comparative impact of solidification and stabilization was approximately 55 percent that of excavation and hauling in this scenario. The comparative impacts of other variables were also reduced.

Sand mining also has a significant contribution to environmental impacts. In the following example, the sand quantity was assumed to be the same for both remediation alternatives, and all other variables were constant. The comparative differences under this scenario were also reduced

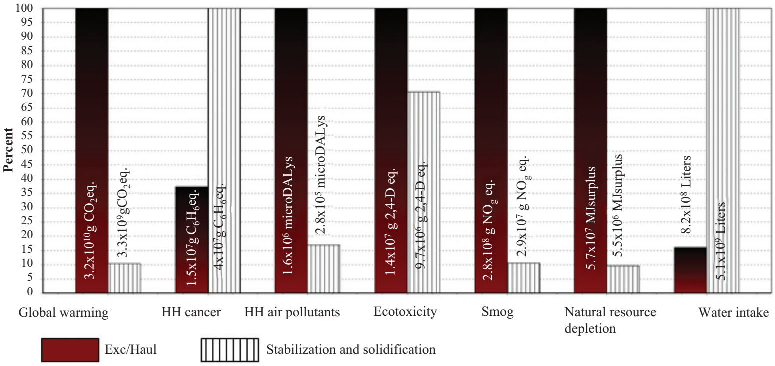


Figure 6.13. LCA comparing excavation and hauling and stabilization and solidification with similar sand mining.

for the variables under consideration. A greater water intake is also required for solidification and stabilization (from water needed for cement mixing).

To further decrease the environmental impacts associated with the solidification and stabilization alternative, recycled materials may be used in place of virgin materials. As an example, slag-cement mixtures have been applied to solidification and stabilization programs for site remediation. One example is a brownfield remediation site in Appleton, Wisconsin. A mixture of 70 percent slag and 30 percent Portland cement was used to remediate coal tar-impacted soil at a former manufactured gas plant (Slag Cement Association). The addition of slag can greatly reduce the environmental impacts associated with the manufacturing and subsequent use of cement. The distance from the slag source to the project site will remain an important factor to consider; however, if a nearby slag source is present, this option can be an attractive way to reduce environmental impact.

It is interesting to note that in most large sites, the SSEM would result in a higher score for solidification and stabilization due to the limited impact to the surrounding communities during construction. Many of the socioindividual, socioinstitutional, and socioeconomic dimensional benefits cited in the IRM site are identical to this case; in situ stabilization and solidification offers identical advantages in many cases compared to the excavation for these dimensions. The justifications for the scores assigned under the socioenvironmental dimension in the SSEM tool are discussed in the following:

- The process of excavation and hauling incurs greater negative impacts due to increased truck traffic and roadway wear in the surrounding community, impacts from vehicular emissions, noise pollution, and greater consumption of energy and fuel, which consequently results in negative scores for the extent of *greenness* pertaining to the application of this option.

- The use of in situ stabilization and solidification remedial option offsets excessive trucking and associated negative impacts; however, the use of excessive cement quantities in this technique can create a negative impact since the manufacture of cement is an energy-intensive process and can also generate toxic emissions such as mercury, acidic gases, and particulate matter, which are considered to be toxic for human health. This issue can be addressed by incorporating recycled materials as a partial substitute for cement (e.g., slag-cement mixtures).

Figure 6.14 shows the results of SSEM results and these indicate that in situ stabilization and solidification had the highest levels of positive social impacts in all four social dimensions evaluated as compared to the excavation and hauling option. Excavation and disposal was found to negatively impact the socioenvironmental dimension and contributed to approximately equal positive impact as compared to in situ stabilization and solidification under all other social dimensions. The category of *no remedy* option resulted in the highest level of negative social impact (Figure 6.14).

6.3.5 REMEDIATION ALTERNATIVE SELECTION

Based on the analysis of two remediation methods, excavation and hauling and solidification and stabilization, the solidification and stabilization

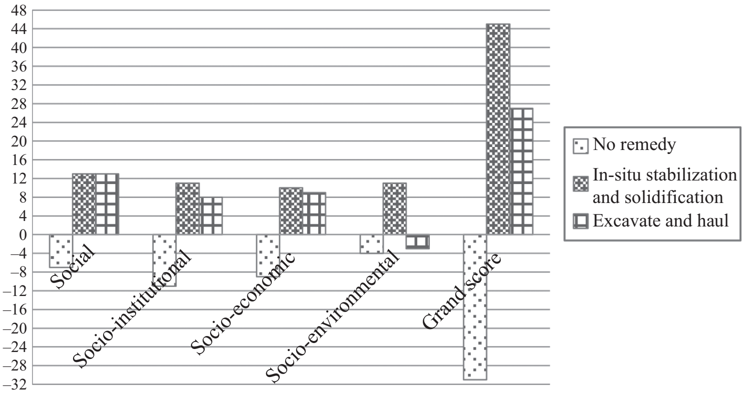


Figure 6.14. SSEM results for Matthiessen and Hegeler zinc superfund site.

method was selected as the superior alternative with respect to sustainability. Largely due to the energy required to transport contaminated waste to a landfill, and also in part to additional clean fill material that would be needed, the excavation and haul option resulted in more environmental impact compared to solidification and stabilization. Excavation and haul did better with respect to potential stressors for cancer-causing agents to human health, largely due to the toxins emitted from the manufacturing of cement.

Several assumptions were used for this particular analysis. Decreasing the distance required to haul waste for instance would yield a lower environmental impact caused by excavation and hauling. At the same time, decreasing the cement application rate or using recycled materials would decrease the environmental impacts associated with solidification and stabilization. Social and economic impacts should be evaluated as well. In this scenario, the large costs and disturbances associated with excavation and hauling would favor solidification and stabilization

6.3.6 CONCLUSIONS

In this application, SimaPro software was used to evaluate the environmental and human health impacts attributed from two possible remediation methods for the Matthiessen and Hegeler zinc smelting site. The site has a long history of production and mining that resulted in large concentrations of heavy metal contamination. In this example, two remediation methods were evaluated using a life-cycle analysis—excavation and hauling, and solidification and stabilization. Solidification and stabilization was identified as a better alternative with respect to sustainability metrics primarily due to energy requirements associated with transport and disposal as well as the transport and placement of clean fill needed to re-establish grades. The excavation option scored better when considering potential stressors of cancer-causing agents to human health, largely due to the toxins emitted from the manufacturing of cement. Ultimately, this analysis indicated that given the large costs and disturbances associated with excavation and hauling, the solidification and stabilization is the more attractive remediation option.

6.4 SUMMARY

Three field applications are presented to document the approach followed to select sustainable remediation technology. Specifically, the sustainability framework, metrics, and tools used for these applications are presented. Of course, some aspects such as social sustainability are not yet fully developed and are subjective. Many field applications and case studies are being published and in a few years, we should have a number of such studies that can help identify the most applicable and useful approaches in selecting the sustainable remediation for given site-specific conditions.

CHAPTER 7

CHALLENGES AND OPPORTUNITIES

7.1 INTRODUCTION

This book has presented a wide range of topics regarding sustainable approaches to environmental remediation. Several challenges associated with the incorporation of sustainability principles to environmental remediation are presented in this chapter. These challenges are focused primarily on a lack of understanding of stakeholders, including project proponents, practitioners, and the general public of the importance of sustainability-based measures with respect to environmental remediation. It is believed that the challenges that exist may be overcome with thoughtful work and contributions from industry, academia, and governmental bodies. With this work, an understanding of these important concepts will surely spark greater interest and implementation.

Because of its innovative nature, its multidisciplinary effects and concepts, and the wide range of stakeholders that are affected, sustainable remediation represents an exciting area of focus for those in the regulatory realm, among practitioners, and those in academia. With the aim of achieving remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water, and soil quality through reduced emissions and other waste burdens, and with an emphasis on conducting such activities in a cost-effective and socially acceptable manner, sustainable remediation offers those with a wide range of perspectives, skills, and experience to participate actively. The continued development of sustainable remediation frameworks, metrics, and assessment tools, including many presented in this book, will further positive benefits to the environment, society, and economy.

7.2 THE BACKLASH OF "GREENWASHING"

As specifically applied to remediation, *greenwashing* refers to situations where sustainable remediation options have not been evaluated and backup documentation is lacking but claims exist that sustainable remediation approaches have been implemented. Greenwashing in a larger sense is commonly associated with a wide range of approaches, from consumer product marketing to legislative initiatives in which suspect *green* or sustainable claims are made. These claims may be misleading or outright false. Specific to the remediation industry, greenwashing is frequently encountered in the marketing of a single, specific remediation technology as *greener* than other remedy options.

Greenwashing claims often serve to erode the confidence of the general public or make the public loath to believe or trust claims of any green or environmentally focused virtue, whether true or false. Similar to greenwashing, misuse of the terms *sustainable* or *sustainability* may hamper the integration and acceptance of sustainable remediation concepts into the environmental industry.

In the future, the potential for *greenwashing* may be lessened through the development of certification processes modeled after existing processes and systems such as the U.S. Green Building Council's (U.S. GBC) Leadership in Energy and Environmental Design (LEED) certification process (U.S. GBC 2011) or the Institute for Sustainable Infrastructure's (ISI) Envision™ rating system. The sustainable remediation concept is likely to gain acceptance, use, and credibility through the development of such a certification.

7.3 LACK OF FINANCIAL INCENTIVES OF SUSTAINABLE REMEDIATION

While there is growing general interest in sustainability concepts, there may be resistance in incorporating a greater degree of sustainability among select potential stakeholders. In many cases, it is associated with cost and timing considerations. With limited exceptions, few financial incentives exist for stakeholders (especially project proponents) to incorporate sustainability principles. As an example, outside of the realm of remediation, there has been a growing general interest in LEED accreditation with respect to building design and construction. However, the interest in the overall goals in LEED and the specific measures that may be employed have not been universally adopted or pursed. Higher levels of LEED accreditation are often pursued and achieved in the design of public or government buildings. A perception exists among many taxpaying citizens that only publicly funded projects are capable of absorbing the additional cost burden associated with incorporating such measures. Defenders will counter that many design features implemented to achieve LEED status result in reduced operational costs that are easily recoverable during the design life of the structure. Critics will further counter that the hold period of many for-profit structures does not provide an adequate time horizon for the original owner to recognize the operational cost savings to justify their use. Further, the general consumer, while valuing general sustainable principles, may not stay true to their beliefs with high-cost purchases or investments like a house when lower-cost alternatives that do not try to achieve a degree of sustainability through design and construction are available in the marketplace.

Adoption of sustainable remediation concepts can face the same resistance. In many locales, project entitlement and approvals can be lengthy, such that when the time comes for a developer to implement a remediation project, timing can often be the major driver in selecting a remediation alternative. This is often the case even if a more sustainable remediation alternative is available for a lower cost. In the absence of the right incentives, project proponents will often select based on remediation duration or cost while accepting the detrimental effects to the environment. A simple solution to a redevelopment green and sustainable remediation (GSR) challenge such as this is the incorporation of GSR evaluations or approaches in the credit and application process for redevelopment grant funders. Local redevelopment authorities have the opportunity to incorporate GSR processes into their grant applications and give credit to those projects willing to evaluate and implement the GSR aspects of remediation on redevelopment sites.

A powerful means to overcome this decision-making inertia is through the use of financial incentives that may be available to a project proponent to use if a remediation alternative is selected based on their strong performance with respect to sustainability metrics. One framework may be through the use of tax-related deductions, credits, or incentives related to environmental or social dimension-related benefits. Another potential framework could be based on the former U.S. Environmental Protection Agency (U.S. EPA) Brownfields Tax incentive program that expired in December 2011. With the program, certain remediation activities associated with brownfield redevelopment could be expensed in the year that remediation activities occurred as opposed to the standard tax treatment of capitalizing the remediation-related costs. By allowing these costs to be treated as expenses, project proponents were able to significantly reduce their tax burden in the year in which they were applied to the proponent's financial statements. Although it is unfortunate that the U.S. government allowed such a valuable financial incentive to expire, a similar framework could be revived that would allow for sustainability-related actions to have a favorable tax effect.

An additional and poignant opportunity for overcoming the challenge of incentivizing sustainable remediation practices lies in the authority of the reimbursement funds common to many state petroleum cleanup programs. These reimbursement fund organizations hold the ability to incorporate the reimbursement of expenses related to sustainable remediation work into their allowable and reimbursable expenses. Often the reimbursement fund organizations may be capable of reaching across the aisle to their constituency to assist in achieving corporate sustainability objectives and at the same time provide financial assurance to the remediation practitioner that the effort put forth in a sustainable remediation evaluation and implementation would be eligible for reimbursement. This type of financial incentive displaces the presumed up-front cost apprehension and perception. At the same time, this authority would negate the policy change necessity within regulatory bodies for sustainable remediation requirements.

7.4 LACK OF A REGULATORY MANDATE

In contrast to many for-profit project proponents, many local, state, and federal agencies are quite enthusiastic and receptive regarding the incorporation of sustainability-based principles into site remediation. First, social-based dimensions are heavily emphasized in many government-sponsored projects. Often this takes the form of hiring goals for disadvantaged business enterprises (DBEs) for direct and indirect project roles. Second, federally funded projects that require the preparation of environmental impact statement (EIS) reports must analyze a given project's effects on the social and economic dimension. Further, as demonstrated throughout this book, several state and federal regulatory agencies have developed sustainability tools, databases, and frameworks to be used to assess various sustainability metrics and dimensions associated with remediation projects. These efforts offer clear evidence regarding a growing interest and emphasis in sustainability principles among these agencies.

While these agencies encourage sustainability-focused activities and efforts, no clear mechanism requiring the incorporation of such measures exists as applied to many remediation projects. Incorporation of best management practices (BMPs) and other activities that enhance the dimensions of sustainability in many cases are optional. With many agencies, the use of such measures may be encouraged, but in many cases these activities are not required.

One consideration to encourage sustainability-focused practices would be through regulatory requirements or mandates. Of course, such efforts would be viewed as controversial and would meet resistance among many potential project stakeholders; however, governmental regulatory activity is present in many aspects of environmental protection. Regulatory agencies oversee the operation of landfill facilities and are intimately involved in the protection of air, land, and water quality. Because the remediation of contaminated properties will invariably have side effects on all these physical media, and in many cases add to the waste stream that eventually affects wastewater and landfill loading, it is appropriate for these governmental agencies to have a say in how remediation and the related waste generation may affect these resources and associated facilities.

7.5 LACK OF PUBLIC AWARENESS

Government mandates requiring specific actions associated with any type of activity or behavior are by their very nature controversial. In a free society, such mandates are almost assuredly met with pushback or protest solely on the basis of governmental requirement. However, in a free society, the government is vested with power from and wields power on behalf of the citizenry. Stated another way, if a particular ideal is the will of the people, it will be encouraged by government.

Despite the virtues of government-based incentives or mandates (the proverbial *carrot* or *stick*) that would encourage the application of sustainability-focused activities or practices for site remediation, the government will not act in such a manner if it is not the will of the public. In many ways, the general public is as aware as ever of environmental issues. These issues may be on a local level—growing interest in local environmentally focused activities like recycling of household waste, to the largest, most complex global environmental issues, such as climate change and its various physical manifestations on the physical environment. However, with respect to remediation, much of the general public is unaware of general remediation activities, let alone the virtues of incorporating sustainability-based practices into site remediation. However, with educational outreach, the public could undoubtedly see the benefit of such practices—reduced use of landfills, less wear and tear on transportation infrastructure, less air emissions, a greater use of renewable energy sources and reclaimed water with reduced reliance, and use of fossil fuels and fresh water sources, to name a few. Once the connection is made for the public of the overall holistic benefit of these practices, it would be reasonable to expect that the public would expect their elected lawmakers and related governmental agencies to put incentive programs and statutory mandates in place to encourage and require such beneficial activity.

7.6 LACK OF SPECIALTY TRAINING ON LCA, CARBON BALANCE, AND OTHER ASSESSMENT TOOLS FOR PROFESSIONALS

For many reasons, it is understandable that the general public is not familiar or aware of traditional or sustainability-related remediation activities. Despite their enthusiasm, regulatory agencies currently lack encouragement of the use of remediation methods that incorporate sustainability principles. Environmental remediation professionals clearly and obviously could play the greatest role in advancing the uses of these remediation practices and activities. However, in many ways, they are unaware of the best means by which to do so. By many measures, they are well aware of the benefits of sustainability practices, but they either are unable to synthesize a remediation project that can utilize these practices, or far more commonly, they lack the knowledge or ability to demonstrate to project stakeholders the benefits of incorporating such principles and practices into remediation projects.

Many remediation professionals do have a desire to incorporate sustainable measures into remediation projects; however, in many cases, they lack the skill set or knowledge of assessment tools to demonstrate the related benefits. With the continued evolution and innovation of these tools, it is necessary for design professionals to seek out and learn these tools so they may be able to apply them on remediation projects. Importantly, as regulatory agencies, public–private partnership entities and academia develop sustainability assessment tools, they need to find better methods to promulgate their tools so that they may be adopted and implemented on a wide scale. A clear understanding of the tools that are available as well as their best-case applicability and limitations is necessary for their widespread use among remediation design professionals. In doing so, it is reasonable to expect that such tool utilization would result in a rapid acceleration in the incorporation of sustainability principles in remediation projects.

It is a natural question to ask how best to encourage awareness, learning, and adoption and use of sustainability assessment tools. There is a wide range of acceptable means. Of course, it may begin with traditional *classroom* work in the form of college courses or continuing education short courses. Utilizing the technical realm, webinars and webcasts, online videos, social media platforms for idea exchange, and other similar channels can reach a wide audience and offer an approachable and convenient means to promulgate the assessment toll concepts. Similarly, case studies and success stories (as well as less desirable lessons learned) may be shared via a wide range of electronic communications and social media outlets.

Beyond the need for trained regulatory professionals is the need for demonstrable returns from case studies showing the use of the sustainable remediation concepts and tools. Currently, the previously named U.S. organizations active in the sustainable remediation realm continue their efforts to gather adequate success stories and disseminate the information across a broad but segmented industry. While many case studies are in development at the state or federal agency level, the private sector appears to have surpassed the waiting game for policy requirement change and in doing so it has created a number of proprietary sustainable remediation tools and methodologies for their own clientele base in the meanwhile. This has resulted in further dissolution of consistent, standardized, and transparent case study sharing across the industry. Frequent sharing of case study results are demonstrated across the country at various symposia, but equal to the number of presentations is the ambiguity of the background data and tool development. These proprietary tools and case studies gain experience for the consulting professional and responsible party but do little to aid in industrywide use and acceptance of sustainable remediation tools and processes and, at worst, increase the distrust of the regulatory community to embrace the data provided. Simply put, the regulator has nowhere to put and no way to process individualized data. Therefore, many of these case studies will remain exercises in futility for the public and entire stakeholder group.

7.7 GREATER ACADEMIC FOCUS

Many innovative remediation technologies that are commonly employed by remediation professionals were conceived of and developed in academia. In this setting, potential technologies can be developed in bench-scale settings with refined mathematical and physical modeling. This naturally feeds into pilot field-scale testing to determine the efficacy of evolving technologies in real-world conditions, and the continued collaboration of academia allows for a deeper understanding of the inherent processes and physical phenomena at work, leading to faster optimization and further development.

This academic and practitioner model has worked for countless technological advances and will continue to advance the applications of environmental remediation. With a greater emphasis of sustainability as a common interest between academia and practitioners, sustainability-related applications would also be expected to evolve at an accelerated pace. First, practitioners and academics do need to identify research needs for sustainable technologies. This could take many forms and areas of interest, from actual remediation applications, material development, or advances in reagent or substrate delivery to means of measurement, computation, modeling, and assessment. Once these common areas of interest are identified, academics and practitioners should closely collaborate on scoping research projects. This would serve the dual goal of targeting specific areas that could benefit most directly from research and lead to related improvements in practice applications as well as facilitate research funding via grants from industry and government. By identifying specific common areas of interest, practitioners and academics can work together to more efficiently devote financial resources to such areas that will yield improvements in sustainable technology deployment and operation.

7.8 FURTHER REFINEMENT AND DEVELOPMENT OF ASSESSMENT TOOLS AND FRAMEWORKS

As discussed earlier, continued and expanded research partnerships between academia and practitioners in industry would result in accelerated advances in remediation technological development and a dual advancement of the state-of-the-art and the state-of-the-practice. Further, such research collaboration could also advance another key concept related to sustainability—the means to accurately measure and assess sustainability-related principles and practices associated with environmental remediation.

As presented throughout this book, numerous assessment frameworks and tools are available for use, both in the public domain and as proprietary, fee-based software. Frameworks have been developed by a number of private and public entities that can provide feasibility-level screening, alternatives analysis, or BMP selection. The range and scope of tools are wide—some are quite simple to use, but do provide limited output.

Other tools are quite complex and can incorporate significant computational capabilities. However, in many cases, these software applications do require a level of expertise to properly use—or at least have an appreciable learning curve that must be overcome in order to yield accurate, actionable results.

The wide range of tools should be viewed as beneficial; because such a range exists, those performing analysis of remediation project sustainability have a wide range of tools at their disposal and may match up the right application for the task at hand. Simple tools may be selected for simple projects or optimization and screening tasks that may be minor in scope. Comprehensive tools may be selected and implemented for more complex projects, when a wider range of analysis is necessary to satisfy project stakeholders on high-visibility projects, or when project impacts can have significant environmental, economic, or social consequences. However, with the wide range of tools, there is significant variation among the actual assessment methods, algorithms, or computational procedures among the range of assessment tools. It is obvious that this would be the case when comparing simple qualitative assessment tools with the most complex life-cycle assessment (LCA) tools; however, even those tools that are used to analyze similar projects in scope can vary significantly.

This variation exists for several reasons. First, different methods place a varied emphasis on parameters associated with different sustainability indicators and metrics under consideration. Some indicators and metrics are heavily emphasized in some tools, while others may be omitted or downplayed. This may extend to the depth and detail required for a given parameter at the input stage or the manner in which related output is reported. Some tools allow for virtually every remediation method to be incorporated into an analysis as long as related activities can be defined and metrics can be quantified, while other assessment tools have been *hard wired* to provide the detailed analysis of a select group of remediation methods. Further, when computations are made during the analysis, equivalent reporting units for associated impacts vary among assessment tools, leading to difficultly in attempting to make a direct comparison of output generated during analyses of identical activities using different assessment tools.

A move toward standardization, at least among similar assessment tools and frameworks would be beneficial to the environmental remediation practice. Even if differences among computational processes within different tools remained, increased standardization in terms of reported output units, indicators and metrics considered, and greater agreement on the range of remediation activities that could be handled by different remediation tools would eliminate confusion. Practitioners would likely feel more comfortable if a common *language* or feel regarding sustainability analysis could be developed; the greater ability for direct comparison among different assessment methods could foster greater interest, trust, and reliance in the tools and the resulting analysis conclusions. It would also enhance innovation and increased accuracy in assessment tools, as increased familiarity of the inputs and outputs would likely result in a greater focus on interest in refinement and enhancement, with an emphasis on identifying new metrics or subanalyses while purging unnecessary data and computations. This move toward uniformity or standardization could be jointly undertaken by practitioners and academia to identify needs, develop solutions, and continuously improve the quality of analysis frameworks and tools.

7.9 IMPROVED ASSESSMENT OF INDIRECT CONSEQUENCES

The lack of uniformity among assessment frameworks and tools presents difficulties when attempting to assess direct project impacts and related benefits or adverse consequences. However, in many cases, it is as problematic or even more difficult to account for indirect benefits or impacts associated with a remediation project. These indirect consequences, whether beneficial or detrimental to the environmental, economic, and social dimensions associated with a remediation project, can be quite extensive and significantly wider in scope than more easily definable direct consequences.

The difficultly in accounting for these indirect benefits exists for two primary reasons. First, system boundary selection will invariably affect the number of indirect consequences that are accounted for in an analysis. While reflexively one might say that a wider system boundary would be more useful because a greater number of impacts could be determined from an analysis, system boundary expansion leads to a significant increase in the complexity and difficultly of an analysis, in terms of both time and cost associated with the analysis. It is not always evident or obvious where to draw a boundary such that diminishing returns associated with increased impact analysis can be readily determined such that they may be excluded from an analysis.

The second reason is that indirect consequences are not often properly accounted for by existing assessment tools, regardless of the choice of system boundary. Straightforward benefits such as reduced emissions, resource utilization, or construction jobs created by a remediation project would be considered typical and easily handled by a comprehensive analysis tool. However, benefits such as increased neighborhood tax receipts, increased life expectancy for residents near a project site, or increased number of species present in a rehabilitated natural habitat can be difficult to quantify with existing tools. As is the case with enhanced assessment tools, practitioners and academia could successfully collaborate to identify key indicators and metrics of indirect benefits resulting from sustainability-focused remediation projects as well as ways to incorporate and quantify into existing and future assessment tools.

7.10 IMPROVED METRICS AND TOOLS TO ADDRESS SOCIAL ISSUES

Regardless of the accuracy or completeness of their scope, inputs, and computation, existing frameworks and assessment tools have mostly been focused on environmental and economic dimensions. As a result, social dimensions have not received much attention. Many assessment frameworks and assessment tools have been developed by economists or environmentally focused entities, such as regulatory agencies. It is natural that the focus of these developments was directed toward economic and environmental dimensions, as these served as the initial impetus for the development of tools and frameworks by these entities. Additionally, as assessment frameworks and tools evolved, the focus was primarily placed on environmental and economic dimensions because metrics associated with these dimensions were relatively easy to quantify and analyze. Further, whether associated on costs or physical units, economic and environmental metrics are relatively easy to objectively compare among remediation project alternatives.

While there has been a general interest in the measurement of social-related sustainability impacts, tools and frameworks other than those cited in this book have been lagging behind the development of other more economically and environmentally focused tools. Metrics for social aspects have been more difficult to develop, as have related units of measurement. However, with increasing interest in these metrics, a greater awareness within the general public of the potential socially related enhancements of site remediation, and increased attention from governmental bodies, academic institutions, and among practitioners in industry, it is reasonable to assume that increased attention and effort will be directed toward the development of social metrics and assessment tools in the near future.

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This book presents a holistic approach to remediation that considers ancillary environmental impacts and aims to optimize net effects to the environment. It addresses a broad range of environmental, social, and economic impacts during all remediation phases, and achieves remedial goals through more efficient, sustainable strategies that conserve resources and protect air, water, and soil quality through reduced emissions and other waste burdens.

Inside, the authors simultaneously encourage the reuse of remediated land and enhanced long-term financial returns for investments. Though the potential benefits are enormous, many environmental professionals and project stakeholders do not utilize green and sustainable technologies because they are unaware of methods for selection and implementation. This book describes the decision framework, presents qualitative and quantitative assessment tools, including multi-disciplinary metrics, to assess sustainability, and reviews potential new technologies.

Krishna R. Reddy, PhD, PE, is a professor of civil and environmental engineering and the director of Sustainable Engineering Research Laboratory and Geotechnical and Geoenvironmental Engineering Laboratory at the University of Illinois at Chicago (UIC). Dr. Reddy received his PhD from the Illinois Institute of Technology in Chicago, and he is a licensed professional engineer in Illinois. Dr. Reddy has over 25 years of research, consulting and teaching experience. He has published over 300 technical publications on various topics on pollution control and remediation.

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