POTENTIAL TECHNOLOGIES FOR REMEDIATION OF BROWNFIELDS

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ABSTRACT: It is estimated that over 500,000 brownfield sites exist throughout the United States. Many of these sites offer attractive financial opportunities, but a major obstacle to their redevelopment is fear of contamination and associated liability. Fortunately, numerous initiatives and regulations have been developed by federal, state, and local agencies to assist and encourage redevelopment of these sites. As a result, over 100 pilot studies have been successfully completed and have demonstrated the economic and social advantages of brownfield redevelopment. A systematic approach to the redevelopment of brownfield sites is crucial in order to control the costs associated with remediation and to accelerate the redevelopment process. This approach includes a phased site characterization, an impact assessment, and a site-specific remedial strategy. Unlike many Superfund and Resource Conservation and Recovery Act corrective action studies, brownfield sites pose unique problems because many are located in heavily populated urban areas. Therefore, additional attention must be paid to using site characterization and remedial methods that will accommodate the often inflexible nature of urban sites. This paper first presents the current state of brownfields, followed by brownfield initiatives and regulations of various regulatory agencies. Next, a rational remedial strategy useful for the guidance of brownfield redevelopment is presented. Because the remedial strategy often requires the application of a remedial method to address site contamination, different remedial technologies are discussed, as well as their applicability to various field conditions. It is anticipated that this assessment of innovative remedial technologies will benefit environmental and geotechnical professionals who may be involved in the rehabilitation of brownfield sites.

INTRODUCTION

Brownfields are abandoned, idled, or underutilized industrial or commercial sites where expansion or redevelopment is complicated by actual or perceived environmental contamination. Brownfields may be as small as a vacant city lot or as large as an abandoned manufacturing facility occupying several hundred acres. The extent of contamination encountered at brownfield sites may range from minor surface debris to extensive, dangerous soil and ground-water contamination. Depending upon the level of contamination, and cleanup standards of the project, remedial costs may range anywhere from thousands to millions of dollars (''Brownfields'' 1995). As a result, sites worth less than $5 million redeveloped are typically not of interest (von Rosenberg and Mankowski 1998). Whether the problems posed by the site are real or exaggerated, the potential danger of financial liability and lengthy litigation often deters prospective buyers and lenders from investment.

While it is nearly impossible to determine the exact number of brownfields within the United States, the U.S. General Accounting Office estimates that up to 500,000 brownfields exist nationwide based on records of past and current commercial and industrial locations. With such an extensive number of sites throughout the country, it is obvious that the existence of brownfields affects virtually every community in the nation (''The preamble'' 1997).

In contrast to a brownfield, a greenfield is a pristine, underdeveloped area that has remained free of industrial and commercial activity. The threat of contamination presented by greenfields is much lower than that presented by brownfields or other urbanized sites. The benefits provided by brownfield redevelopment are intimately connected to the benefits of refraining from further greenfield development. By discouraging development within greenfield areas, suburban sprawl is reduced, effects of potentially increased traffic congestion are lessened, natural wildlife habitats are protected, and the abandonment of cities and inner rings of suburbs may be reversed. Concerning the communities in which brownfields are located, redevelopment may improve community appearance and image, relieve associated health and environmental concerns, and produce a beneficial economic effect through increased property values and employment opportunities.

Many factors influence a decision regarding the purchase and development of property. A single concern about environmental contamination at a site is often enough motivation to prevent an acquisition and development project. Yet such concern about potential brownfield redevelopment is often unwarranted. Even if contamination exists at an otherwise attractive site, many remediation technologies exist that make brownfield redevelopment a viable and cost-effective option. These technologies are often simple, fiscally responsible, and highly effective. However, since many of the technologies are recent innovations, experience in their use is often lacking. As a result, they may be applied incorrectly or at an unsuitable site, thereby exacerbating the contamination problem. Therefore, it is important to have an understanding of the behavior and application of the available remedial technologies that may be implemented at brownfield sites (Reddy et al. 1997). The objective of this paper is to outline the brownfield redevelopment process as well as provide a background and assessment of selected methods used to remediate contaminated soils and ground water.

BROWNFIELD INITIATIVES AND REGULATIONS

In 1980, the U.S. Congress established the Superfund program to provide the financial assistance needed for the remediation of hazardous waste sites that pose serious risk to the health and safety of the public as well as the welfare of the environment. The Superfund program is administered by the U.S. Environmental Protection Agency (USEPA) in cooperation with regional governmental agencies.

In order to determine which sites are eligible to receive federal aid under the Superfund program, a ranking system has been established to allow for a quantitative rating of sites across the United States. Sites that score high enough on USEPA's hazard ranking system are placed on the National Priorities List, a published list of hazardous sites that require

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extensive, long-term remediation and are deemed eligible to receive funding from the Superfund program. If site contamination is determined to be extensive in nature, certain brownfield sites may fall within Superfund jurisdiction. Even minor rehabilitation efforts of brownfield sites that fall under such jurisdiction must comply with the stringent remediation codes, liability standards, and documentation required by the Superfund program.

Unfortunately, sites that fall under Superfund jurisdiction offer two substantial obstacles that may prevent their consideration as brownfields. First, purchasers of contaminated sites may be held responsible for damage caused by previous owners even if sites were contaminated by legal activities at the time of occurrence (''United'' 1997). This obviously may discourage parties from acquiring a site that may be considered a possible brownfield project. Additionally, Superfund regulations require that a contaminated site be remediated to very low contaminant levels such that risk to public health is minimized. Such an approach is often inflexible and does not take into account the intended use of the rehabilitated site. The financial effects of such regulations may also eliminate the feasibility of many brownfield projects.

Reforms and amended regulations have been proposed to lessen the severity that Superfund regulations have on brownfield projects. For example, the State of Illinois recently signed a Superfund Memorandum of Agreement with USEPA stating that USEPA will not pursue liability claims on sites that have successfully completed Illinois' Site Remediation Program. Additionally, 11 states have drawn up memoranda of agreement with USEPA that provide for expedited cleanup under the auspices of state and local government (Harrigan 1998).

Aside from its administration of the Superfund program, USEPA has numerous initiatives specifically geared toward brownfield development. The most relevant USEPA programs for brownfield development include the brownfields pilot program and recent developments regarding treatment of brownfields that fall under Superfund jurisdiction.

In 1993, USEPA launched the brownfields pilot program with a $200,000 grant used for a contaminated site in Cleveland. The purpose of the grant and the program as a whole was to create a model for brownfield redevelopment that could then be duplicated throughout the country. The program has continued in order to obtain practical experience in site remediation as well as for the development of innovative strategies for environmental remediation policy. Since 1993, brownfield grants totaling more than $42 million have been awarded to states, cities, counties, and tribes (Canning and Harrigan 1998). Each of these sites is provided with a maximum grant of $200,000 (Larsen 1997). This assistance is used to perform initial site audits as well as site characterization in order to assess the degree of site contamination.

Additionally, with the realization that Superfund regulations often limit the remediation of brownfield sites, USEPA has recently clarified several liability and remediation issues related to brownfields. Many of these issues focus on the release of lending institutions from liability of any problems that may result from a brownfield site. With the elimination of financial risk, lending institutions are more inclined to support the redevelopment of brownfield sites, thus providing faster remedial action.

Aside from amending liability and remediation issues, USEPA is also working in concert with other federal agencies to promote brownfield remediation and redevelopment. Alliances have been formed between USEPA and the Departments of Labor, Housing and Urban Development, Defense, and Energy. The relationships formed between these agencies are intended to promote job training, housing opportunities, and other opportunities which may result from brownfield redevelopment.

Many state governments are also assisting in brownfield redevelopment. Nearly half of the states in the United States offer some type of voluntary remediation program. The purpose of such programs is to encourage remediation of sites with possible contamination while preventing any increased liability for participating parties. When a remediation project is completed, many states will issue a statement releasing the participants from state liability for any contamination that may exist at the site. Often state agencies will offer assistance to project participants if they are subject to federal liability.

REMEDIAL STRATEGY

A systematic approach for the assessment and remediation of brownfields is necessary in order to facilitate the brownfield redevelopment process and avoid undue delays. The most important aspects of the approach include (1) site characterization; (2) impact (or risk) assessment; and (3) the selection of an effective remedial action. Fig. 1 outlines this systematic approach. This comprehensive approach is similar to that required for the remediation of Superfund sites. In the case of brownfield development, however, innovative integration of these tasks can often lead to a faster, cost-effective remedial program.

Site Characterization

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

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

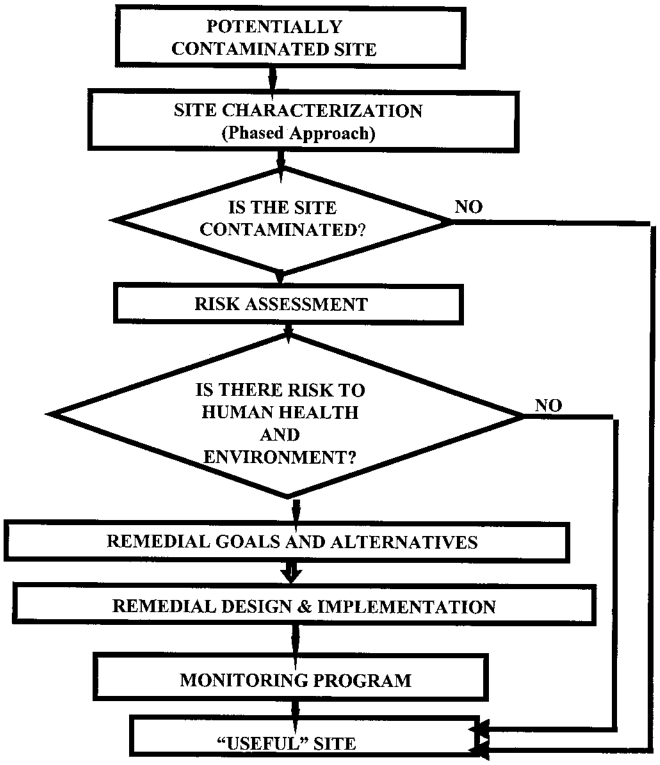

FIG. 1. General Approach for Brownfield Site Assessment and Remediation

duration of possible remedial action, or extensive contamination problems resulting from inadequate or inappropriate remedial action. Site characterization is often an expensive and lengthy process; therefore, it is advantageous to follow an effective characterization strategy to optimize efficiency and economy.

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, and distribution. 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 financial impact by improving the planning of the investigation and ensuring the collection of relevant data. Phase I consists of the definition of investigation purpose and the performance of a preliminary site assessment. Phase II is performed in order to obtain preliminary information regarding site conditions. Phase III includes a detailed site investigation in order to define site geology, hydrogeology, and the contamination profile. If data collected after the first three phases is determined to be inadequate, a fourth phase should be developed and implemented to gain additional information. The entire phased approach must be repeated until all pertinent data have been collected.

Depending on the logistics of the project, site characterization may require regulatory compliance and/or approval at different stages of the investigation. Thus, it is important to review the applicable regulations during the preliminary site assessment of 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/or approvals.

A preliminary assessment of the project site is a crucial step in the site characterization process. It provides the geographical location, background information, regional hydrogeologic information, and potential sources of contamination pertaining to the site. The preliminary site assessment consists of two tasks: a literature review and a site visit. The results of these tasks form the basis for an exploratory site investigation (phase II).

Based on the results of the phase I activities, the purpose and scope of the exploratory site investigation needs to be developed. If contamination was detected at the site during the course of the preliminary investigation, the exploratory site investigation must be used to confirm such findings as well as obtain further data necessary for the design of a detailed site investigation program. 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/quality control (QA/QC) plan, a health and safety (S&H) plan, a work schedule, and a cost assessment.

The detailed site investigation is performed to characterize the geology, hydrogeology, and contaminant type and distribution at the site. The data gained from the detailed investigation must be compelling enough to properly assess the risk posed at the site as well as allow for effective designs of possible remedial systems. As with the exploratory investigations, a detailed work plan including field and laboratory testing programs as well as QA/QC and S&H plans should be outlined. 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 the effort required, this phase of the investigation is very costly.

Impact (or Risk) Assessment

Once site contamination has been confirmed through the course of a thorough site characterization, an impact assessment is performed. An impact assessment, also known as a risk assessment, is a systematic evaluation used to determine the potential risk posed by the detected contamination to human health and the environment under present and possible future conditions. If the impact 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.

USEPA and ASTM have developed comprehensive impact assessment procedures. The USEPA procedure was originally developed by the U.S. Academy of Sciences in 1983. It was adopted with modifications by USEPA for use in Superfund feasibility studies and Resource Conservation and Recovery Act corrective measure studies (RISK 1989). This procedure provides a general, comprehensive approach for performing impact assessments at contaminated sites. It consists of four steps: (1) hazard identification; (2) exposure assessment; (3) toxicity assessment; and (4) risk characterization. ASTM E 1739-95, 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 (Annual 1997). Although the standard is geared toward such sites, many regulatory agencies use a slightly modified version for sites that do not contain underground storage tanks. This approach integrates risk and exposure assessment practices with site assessment activities and remedial measure selection. 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.

Remedial Action

When the results of an impact 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, 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 ground-water characteristics. The selected method must be able to address site contamination while offering compatibility with the geology and hydrogeology of the site. Because many prospective brownfield sites are located within urban environments, a remedial method must be compatible with characteristic urban site conditions, including surrounding buildings and utility infrastructure. Because real estate market demands are often the catalyst behind brownfield redevelopment, site remediation must occur in a timely manner in order to capitalize on its useful economic contribution. Most importantly, the economics of site remediation must be considered to assure that redevelopment offers a viable economic option to development elsewhere. Therefore, the predicted cost of the remedial project must not exceed the estimated value of the remediated site. Incorporation of these basic guidelines into the remedial strategy often facilitates the selection of an optimal course of action.

Generally, remediation methods are divided into two categories: in-situ remediation methods and ex-situ remediation methods. In-situ methods treat contaminated soils and/or ground water in-place, eliminating the need to excavate the contaminated soils and extract ground water. In-situ methods are advantageous because they often provide economic treatment, little site disruption, and increased safety due to lessened risk of accidental contamination exposure to both on-site workers and the general public within the vicinity of the remedial project. Successful implementation of in-situ methods, however, requires a thorough understanding of subsurface conditions.

Ex-situ methods are used to treat excavated soils and/or extracted groundwater. Surface treatment may be performed either on-site or off-site, depending on site-specific conditions. Conditions characteristic of urban settings, including neighboring buildings and narrow streets, often limit the use of on-site treatment facilities. Therefore, off-site treatment requiring transport of contaminated materials to a treatment facility is often necessary at urban brownfield sites. 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.

REMEDIAL TECHNOLOGIES

Remedial technologies are classified into two groups based on their scope of application: (1) vadose zone technologies and (2) saturated zone technologies. The vadose zone is the geological profile extending from the ground surface to the upper surface of the principal water-bearing formation. Remedial measures implemented before the onset of ground-water contamination at a particular site may lessen the financial impact of the remediation program. A number of remedial technologies are suitable for vadose zone treatment; however, many of these options are not capable of treating contaminated ground water. In the case of saturated zone contamination, other technologies must be considered for possible implementation. To properly remediate subsurface contamination, it is essential to understand the operation, applicability, advantages, and drawbacks of available subsurface remedial technologies.

Vadose Zone Remediation Technologies

A major concern at brownfield sites is the possibility of vadose zone contamination that has the potential to infiltrate the underlying ground-water resources. Fortunately, remedial measures may be implemented within the vadose zone before the onset of contaminant migration into the saturated soil profile and ground water. The most common practice used to remediate vadose zone contamination is excavation. Simply stated, contaminated soils are excavated from the contaminated site and are subsequently disposed into landfills. 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 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 excavation of contaminated soils is not a feasible option, a number of conventional and innovative methods may be used. These methods may either be in-situ or ex-situ methods. Common remedial methods are summarized in Fig. 2. Table 1 offers a comparative assessment of different in-situ remedial methods (Harsh et al. 1984; Anderson 1993; Nyer et al. 1996; Bernosky 1998; USEPA 1997, 1998a–e), while Table 2 compares several ex-situ technologies [Hazardous Waste Research and Information Center (HWRIC) (1993); Nyer et al. (1996); Bernosky (1998); USEPA (1997, 1998a–e)].

Soil vapor extraction 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. A soil vapor extraction system consists of three basic components: an extraction system, an air flow system, and an off-gas treatment system. By applying a vacuum to the subsurface within the contaminant zone, the extraction system induces the movement of volatile

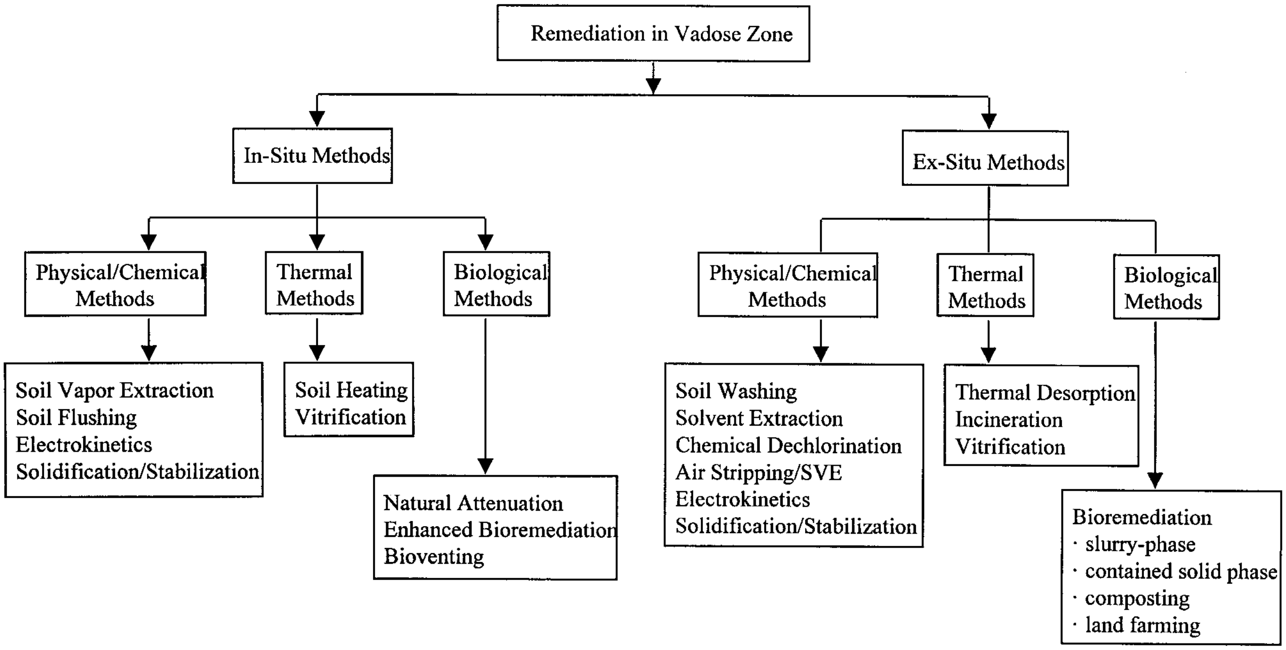

FIG. 2. Common Vadose Zone Remedial Technologies

TABLE 1. Comparative Assessment of In-Situ Soil Remedial Technologies

Technology (1)	Applicability (2)	Strengths (3)	Limitations (4)	Cost range (5)	Commercial availability (6)	Complementary technologies (7)
Soil vapor extraction	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/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 concentration levels; lengthy treatment time; food chain contamination	<$100/ton	Very limited	Bioremediation

TABLE 2. Comparative Assessment of Ex-Situ Soil Remedial Technologies

Technology (1)	Applicability (2)	Strengths (3)	Limitations (4)	Cost range (5)	Commercial availability (6)
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/stabilization	Metals; organic compounds	Proven technology; wide range of contaminants	Organic soils; volume increase; long-term integrity	$50–$250/ton	Widespread

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. Soil vapor extraction systems are relatively easy to install, operate, and maintain, and they are easily integrated with other remedial technologies for remediation projects.

In-situ soil flushing involves the extraction of contaminants from the soil using water or other 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/contaminant solution encounters the water table, it will mix with the ground water, 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 transformation products of the extractants and contaminants from adding to the contamination problem.

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. While soil washing typically uses aqueous wash solutions as extraction agents, a similar technique known as solvent extraction utilizes organic solvents. Examples of such solvents include liquefied gas and triethylamine.

Another technique that requires the introduction of a chemical agent into the subsurface is known as chemical dechlorination. By removing chlorine from chlorinated organic chemicals the toxicity of chemicals such as solvents, pesticides, and PCBs is reduced. This in turn facilitates further contaminant treatment or removal. Caution must be exercised if inorganics are present, as such an occurrence may interfere with the performance of this technique.

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 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 other inorganic species and polar organic contaminants; often, heavy metals may be removed with efficiencies from 75% to 95%.

Bioremediation is an increasingly popular technique during which microorganisms are used 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: natural and enhanced. Natural bioremediation uses naturally occurring aerobic 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 suitable microorganisms and nutrients. Whether natural or enhanced bioremediation is used, the effectiveness of treatment depends upon the type of contaminant(s), the microbial population, and subsurface physical and chemical conditions. Thus, a careful assessment regarding biological as well as nutrient and oxygen conditions 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.

Various thermal methods may be employed to accomplish contaminant remediation. In-situ vitrification 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 power line frequency heating or radiofrequency heating. 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 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 becomes cost-prohibitive once large volumes of soils are treated.

While many remedial techniques rely upon contaminant removal, another technique known as solidification/stabilization transforms contaminants into immobile forms. 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 high-molecular-weight organics.

Saturated Zone Remediation Technologies

If ground-water contamination is confirmed and corrective action is deemed necessary following a thorough site characterization and impact assessment, one of many remedial technologies may be used for corrective action. Some of the aforementioned remedial technologies may be applied to saturated soils, including electrokinetics, soil flushing, and bioremediation. Other popular remedial methods include (1) pump-and-treat; (2) air sparging; (3) dual phase extraction; and (4) reactive walls. Containment methods such as slurry walls and grout curtains are also used to control contaminant plumes within ground water but are not discussed in this paper. Containment methods such as these are often used as interim measures prior to the final selection and implementation of a remedial method. 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 (Anderson 1993; HWRIC 1993; Nyer et al. 1996; Bernosky 1998; USEPA 1998a–e).

Until recently, the most conventional method for ground-water remediation has been the pump-and-treat method. With pump-and-treat, free-phase contaminants and/or contaminated ground water are pumped directly out of the surface. Treatment occurs above ground, and the cleaned ground water is either discharged into sewer systems or reinjected into the subsurface. 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 control of contaminant plume migration.

Air sparging is an emerging 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 in-situ degradation. Eventually, the contaminant-laden air encounters the vadose zone, where it is often collected using a soil vapor extraction system and treated on-site. Air sparging offers best results when 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 required equipment is readily available, air sparging is often an economically attractive remedial choice.

TABLE 3. Comparative Assessment of Ground-Water Remedial Technologies

Technology (1)	Applicability (2)	Strengths (3)	Limitations (4)	Cost range (5)	Commercial availability (6)	Complementary technologies (7)
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 ground water	Widespread	Bioventing; fracturing; horizontal wells
Air sparging	VOCs	Simple; cost effective	Heterogeneous and low K soils	<\$3/gal. of ground water	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 of 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 of 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 of 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

Dual-phase extraction, also known as vacuum-enhanced recovery, is a hybrid remediation technique that combines technology from pump-and-treat and soil vapor extraction. During implementation, ground water is pumped to ground level through the application of a vacuum, allowing for the removal of the dissolved contaminants within the extracted water and 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 and inexpensive and are well suited for aquifers with low permeability.

Reactive walls offer a passive approach for ground-water remediation. In general, a permeable wall containing an appropriate reactive material is placed across the path of a contaminant plume. As contaminated water passes through the wall, the contaminants are either removed or degraded. When designing a wall, not only must an appropriate reactive medium be chosen, but wall dimensions must be designed to assure the entire contaminant plume is intercepted and enough residence time within the wall is allowed for remediation to take place. Reactive walls are often economically advantageous because no mechanical equipment is required, eliminating substantial capital, operating, and maintenance costs.

SUMMARY

Over 500,000 brownfield sites exist throughout the United States; many have been considered for redevelopment (Bartsch 1996). These sites require characterization of potential contamination and possible implementation of remedial action. Some sites may harbor little or no contamination; as a result, their development follows a very simple process. However, other sites may contain dangerous contamination, both at and below the surface. Therefore, the remediation of such contamination is a major issue that must be dealt with before redevelopment can occur. Fortunately, recent policies and initiatives have made brownfield redevelopment an attractive option.

When a contaminated site presents itself as an attractive candidate for redevelopment, it is imperative that an economic analysis be performed to determine whether or not the site is a viable option for redevelopment. If development is deemed to be desirable, it is of the utmost importance to properly characterize the site. Such a characterization includes defining the site's geology, hydrology, contamination, potential releases to the environment, and the locations and demographics of nearby populations. Once the site has been characterized, a risk assessment of hazards at the site is performed and a suitable remedial action may be selected. In order to perform these different tasks in a fiscally responsible manner, it is important that the entire remedial planning, from initial site characterization efforts until the completion of site cleanup, follow a rational strategy.

If contamination has been detected at a brownfield site, an appropriate remedial technology must be selected and properly implemented. This requires a thorough understanding not only of the conditions within the subsurface, but also of the advantages and drawbacks of the available remedial options. Such an understanding is necessary because improper implementation can often exacerbate site contamination. Additionally, because many brownfield sites are located in densely populated urban environments, a critical assessment of possible remedial options must be performed to determine which technologies offer the necessary flexibility to account for site conditions. By possessing knowledge of the available technologies, remediation professionals will be better equipped to use proper judgment for the decisions regarding the development of brownfields.

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