Chapter 8

The Correction of Groundwater Contamination: Technologies and Other Alternatives

Contents

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The Correction of Groundwater Contamination: Technologies and Other Alternatives

CHAPTER OVERVIEW

Correction is broadly defined in this study to include reducing concentrations of, eliminating, or otherwise controlling contaminants in groundwater. This chapter describes the principal technical and management options available for corrective action and analyzes them in terms of their applicability under different conditions, performance, and stage of development. Technical options are categorized under containment, withdrawal, treatment, and in-situ rehabilitation; management options, which may have technical components, are a fifth category. These categories generally reflect differences among alternatives in terms of how and where substances are acted upon.

Although there is a wide variety of alternatives for correcting groundwater contamination, their effectiveness is uncertain. Experience with them is limited, their applicability can be determined only in relation to given site conditions, and their performance over the long term is an unknown. Some technologies are new, but many are commercially available, having been developed for surface water, industrial, and other purposes.

SELECTING A CORRECTIVE ACTION STRATEGY

The principal options available for corrective action are shown in table 34. Although there is a wide variety of options, no one alternative is capable of responding to all conditions likely to be found at a groundwater contamination site. Rather, options tend to address specific hydrogeologic components, objectives, or steps (refer to table 24) in a corrective action process. For example, options in the treatment category assume that contaminated water is already in the treatment system and do not address how it will be removed from the subsurface (e.g., with withdrawal methods). Thus, in practice, alternatives are combined in a *corrective action strategy* to take advantage of their complementarities.

Selecting a combination of alternatives involves making tradeoffs—among time, costs, performance, and other factors—and not all tradeoffs are quantifiable. As yet, there is no standard approach to formulating corrective action strategies, in large part because groundwater contamination is site-specific and experience is limited. Experts contacted for this study stressed the need for a more scientific and less ad hoc approach in applying and tailoring combinations of techniques to sites. Such a methodology would systematically consider site conditions, resource constraints, and performance objectives in evaluating and selecting among alternatives.

Experience appears to show that the selection of a corrective action strategy is not primarily based on lowest costs. Rather, selection appears to be based on how quickly methods can be implemented, how quickly they are expected to achieve desired results, and the uncertainty associated with their performance. Considerations in selecting techniques, which have been identified on the basis of case histories, include: the potential for a public

Table 34.—Corrective Action Alternatives: Techniques and Descriptions[a]

I. Containment: This category consists of geotechnical methods that act to limit the mobility and prevent the further spreading of contaminants. Contaminants are not actually removed from the subsurface but are contained or isolated from the rest of the environment—e.g., via physical barriers or hydrodynamic pressures. Techniques are applied in relation to either the contaminants or their source.

1. *Slurry Wall*: Consists of a material (slurry) barrier wall constructed in-place; is usually located below the water table and surrounding a site to limit the horizontal migration of contaminants in the saturated zone; is also used to reduce hydraulic gradients, facilitate withdrawal, or channelize groundwater flow.
2. *Sheet pile*: Consists of a material (e.g., concrete, steel, or wood) barrier wall inserted into place by driving or vibration; is usually located below the water table and around a site to limit the horizontal migration of contaminants in the saturated zone.
3. *Grouting*[b]: Consists of a material cutoff injected into voids of water-bearing strata either to cover, bottom seal, or bind together the subsurface materials at a site.
4. *Geomembrane cutoff*: Involves the insertion of synthetic sheeting into an open trench (combining aspects of both the slurry wall and sheet pile) to form a barrier wall; is used primarily to limit the horizontal migration of contaminants in the saturated zone.
5. *Clay (or other) cutoff*[c]: Clay (or other material, e.g., concrete) barrier wall; normally is constructed above the water table and downgradient of a site to limit the horizontal migration of contaminants in the unsaturated zone (which is commonly negligible).
6. *Liner*[d]: Consists of a material (e.g., clay or synthetic) barrier constructed or emplaced to isolate (e.g., cover or seal) contaminating sources in order to limit the vertical migration of contaminants; is often a facility design component.
7. *Natural containment*: Involves limitation of contaminant mobility by naturally occurring geochemical, geologic, and/or hydrologic conditions; is evaluated by analytical and/or empirical methods.
8. *Surface sealing*[d]: Is used as an infiltration control measure to limit the vertical migration of contaminants either by reducing leachate production and/or recharge.
9. *Diversion ditch*[d]: Is used as an infiltration control measure to limit surface runoff into a contamination management area (e.g., a slurry-walled area) by channelizing and diverting surface drainage.
10. *Hydrodynamic control*: Limits the horizontal migration of contaminants in the saturated zone through selective pumping and the subsequent creation of pressure troughs or pressure ridges.

II. Withdrawal: Withdrawal options include methods for either directly removing or facilitating the removal of contaminated groundwater and/or contaminated soils from the subsurface. Techniques are principally applied in direct relation to the contaminants.

1. *Pumping*: Involves the removal of contaminated groundwater by pumping from wells or drains; controls the lateral (and in some cases, vertical) migration of contaminants; can be used for flushing (via artificial recharge).
2. *Gravity drainage*: Involves the removal of groundwater from the subsurface using the force of gravity (e.g., using sumps of French drains) instead of pumps; controls the lateral (and in some cases, vertical migration of contaminants.
3. *Withdrawal enhancement*: Enhances the ability to withdraw either groundwater or contaminants, typically by increasing contaminant solubility in water (e.g., by injecting steam or heat, bacteria or nutrients, or surfactants).
4. *Gas venting*: Removes gases associated with contamination (e.g., methane and petroleum-related products).
5. *Excavation*: Involves the direct removal of contaminated soil and/or groundwater resulting from source leakage.

III. Treatment: This category includes physical and chemical/biological treatment methods for detoxifying contaminants found in groundwater. These methods presume that contaminants have already been withdrawn from the subsurface (e.g., via withdrawal methods) in the form of contaminated groundwater or contaminated soils. Treatment can be applied at the source, at the site of contamination (e.g., in on-site treatment units), prior to the distribution of groundwater for use (e.g., in municipal wastewater treatment facilities), and at the point of end use (e.g., at the tap).

a. Physical treatment

1. *Skimming*: Involves the removal of floating contaminants (e.g., oil, grease, and hydrocarbons) in a multi-layer solution.
2. *Filtration*: Involves the physical retention and subsequent removal of contaminants present as suspended solids.
3. *Ultrafiltration*: Involves the physical filtration, through semi-permeable membranes, of suspended and dissolved metals, emulsified hydrocarbons, and substances of high molecular weight.
4. *Reverse osmosis*: Involves the osmotic filtration, through semi-permeable membranes, of contaminants (e.g., metals and radioactive wastes) present as dissolved solids; operates at high pressures (up to 1,500 psig).
5. *Air stripping*: Uses air injection to facilitate the volatilization and removal to the atmosphere of contaminants (e.g., volatile organics and hydrogen sulfide) that are present in water as dissolved solids.
6. *Steam stripping*: Involves the fractional distillation of volatile organics or gases by heating.

b. Chemical/biological treatment

7. *Precipitation/clarification/coagulation*: Removes contaminants (e.g., suspended and colloidal solids, phosphates, and heavy metals) through the use of chemical additives such as coagulants and coagulant aids.
8. *Ion exchange*: Removes selected ions (primarily inorganic) via the exchange of ions between an insoluble solid salt ("ion exchanger") and a solution containing the ion(s) to be removed.
9. *Adsorption*: Removes contaminants (primarily organics) via their tendency to condense, concentrate,

Table 34.—Corrective Action Alternatives: Techniques and Descriptions[a]—continued

or adhere on the surface of another substance (e,g., granular activated carbon and synthetic resins) with which they come into contact.

10. *Electrodialysis:* Separates and removes positive or negative ions under the action of an electrical field.
1. *Chemical transformation:* Involves oxidation-reduction reactions for the chemical conversion of contaminants to less toxic substances (e.g., by ozone treatment, hydrogen peroxide treatment, ultraviolet photolysis, and chlorination).
12. *Biological transformation:* Involves the transformation and removal by micro-organisms of dissolved and colloidal biodegradable contaminants; includes both aerobic and anaerobic processes.
13. *Incineration:* Involves the high-temperature transformation of contaminants into constituent components; many types of thermal destruction systems are included.

IV. *In-situ rehabilitation:* In-situ rehabilitation techniques are directed at immobilizing or otherwise detoxifying contaminants in place.

1. *Biological degradation:* Involves either stimulating the growth of native microflora or injecting specific organisms to consume or otherwise alter contaminants.
2. *Chemical degradation:* Involves the injection of specific chemicals that react with or otherwise alter contaminants.
3. *Water* tab/e *adjustment:* Involves either the isolation of the contaminated zone (and creation of a detoxifying unsaturated environment) by lowering the water table or the artificial inducement of increased flushing action by raising the water table.
4. *Rehabilitation via natural processes:* Involves the natural degradation, dispersion, or detoxification of contaminated groundwater; is evaluated by analytical and/or empirical methods.

V. ***Management option:*** Management options are usually applied either to prevent further contaminant ion or to protect potential exposure points from contaminated groundwater. These methods thus focus on sources and exposure points rather than on the contaminants per se. The methods also tend to be institutionally-based rather than technology-based.

1. *Limit/terminate aquifer use:* Limits access or exposure of receptors to contaminated groundwater.
2. Develop *alternative water supply:* Involves the substitution of contaminated groundwater with alternative supplies (e.g., surface water diversions and/or storage, desalination, and new wells).
3. *Purchase alternative water supply:* Includes bottled water and water imports.
4. Source removal[e]: Involves the physical removal of the source of contamination and includes measures to eliminate, remove, or otherwise terminate source activities; could also include modification of a source's features (e.g., operations, location, or product) to reduce, eliminate, or otherwise prevent contamination.
5. *Monitoring:* Involves an active evaluation program with a "wait and see" orientation.
6. *Health advisories:* Involves the issuance of notifications about groundwater contamination to potential receptors.
7. *Accept increased risk:* Involves the decision to accept increased risk; is usually a "no action" alternative.

aBa~ed on Woodward.Clyde Consultants, Inc, lg83. See this reference for a detailed bibliography on Spec(flc correct ive actlofl alternatives
bean be~on Sidered a form of chemical Immobllizatlon If Injected directly Into the plume of contamination
Cp~ys, cal barriers located above the ~ate~ table Wlll not affect the horizontal mlgratlon of contaminants In the saturated **zone**
d Most often "Sed in the context of either ,~ource removal" or the **prevention** of recharge to the groundwater System. rather than as a **COfltalflmf3flt Optl Ofl per S'**
'Modlf, cat, on of a Source's features ,s often an Important element of corrective action In the context of preventing future ground water contamination (1 e , reducing the need for future corrective action)

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health or environmental hazard, the potential for any hazard to become more serious over time, the potential for loss of public confidence, the potential for liability, and fear of the unknown (Woodward-Clyde Consultants, 1983).

Technical and Non-Technical Conditions Determining the Applicability of Corrective Action Alternatives

The applicability and selection of alternatives for a groundwater contamination problem depend on site conditions. Conditions are technical (e. g., geologic setting, aquifer type, saturation, and type and concentration of substances) and non-technical (e.g., cost, time, safety, and institutional factors). They are described in detail in appendixes F. 1 and F.2, respectively.

There are site conditions that limit all *technology-based* corrective action strategies, assuming a stringent criterion for contaminant reduction, elimination, or control. Among these conditions are: 1) the presence of multiple bodies of contamination at a site and/or complex mixtures of substances; 2) heterogeneous, highly complex aquifers; 3) depths of contamination beyond approximately 20 meters; and 4) the presence of substances that partition (i. e., separate) out of water and are non-biodegradable. The degree to which these constraints effectively preclude application of technology depends to a large extent on whether substances can be withdrawn and treated.

Often withdrawal and treatment are not possible. For example, the application of some withdrawal methods (e. g., pumping) is limited in unconsolidated, fine-g-rained materials of low permeability and may be impractical (in terms of time and costs) if high water volume handling requirements are involved. Individual treatment techniques address specific types of substances, and no single technique is applicable to the mix of substances often found in groundwater. Further, sudden temporal changes in the types and/or concentrations of substances passing through a treatment system can lessen treatment effectiveness. Thus, several treatment techniques would generally be required to treat contaminated groundwater, but even then there is no guarantee that all substances will be reduced to desired levels.

Other conditions that determine and often restrict the applicability of corrective actions to a given site include:

- *hydrogeology, e.g.,* methods requiring construction (many containment methods and excavation) are often technically impractical in hard rock; material barriers depend on the presence of a horizontal stratum of low permeability and sufficient thickness for anchoring; and highly fractured sedimentary or crystalline rock precludes the use of most techniques except pumping, treatment (if withdrawal can be accomplished), and grouting;
- types and concentrations ***of*** contaminants, e.g., special handling and disposal may be required with options involving construction or withdrawal in the presence of certain substances; high concentrations severely reduce the efficiency of withdrawal; mixtures of substances reduce the efficiency of treatment; and multiphase flow (as when substances are immiscible in and denser than water) poses special design and implementation problems for most methods;
- *depth, e.g.,* methods involving construction equipment are generally limited to depths of approximately 20 meters;
- ***environmental and health effects, e.g.,*** health effects are associated with containment and management options that allow the continued presence and potential for continued migration of substances; environmental effects potentially include alterations to existing groundwater flow patterns if construction or pumping is involved and the introduction of biological or chemical agents— and the continued presence of *altered* substances—with in-situ rehabilitation; and some treatment options can have air pollution side-effects (air stripping);
- cost, e.g., depending on site conditions, costs can be tens of millions of dollars or more; containment tends to be capital-intensive during construction and installation with relatively small long-term operation and maintenance costs, while withdrawal is less capital-intensive overall but has significant long-term operation and maintenance costs; and cost considerations have effectively precluded corrective action in areas larger than about O. 1 km^2 and for volumes exceeding about 1,000 m^3; and
- *performance objectives* in terms of the continued presence of substances—e. g., excavation eliminates substances from a site relatively quickly but depends on the availability of an alternative site for disposal of excavated materials; pumping may remove high concentrations of substances in the near term, but decades of pumping may be required before a significant additional reduction is achieved; and treatment may also be required over the long term and removal efficiencies are highly variable.

Appendix F.3 summarizes information about conditions determining the applicability of corrective action alternatives in relation to the OTA source categories discussed in chapter 2 (refer to table 5). Essentially, no technically based corrective action can stop a source from causing contamination: 1) if the source is deep, such as many sources in Category I (i. e., sources designed to discharge substances) and Category V (i. e., sources that provide a conduit); or 2) the source releases substances over a wide area or if large volumes of water are involved, as in Category IV (i. e., sources that discharge substances as a consequence of other

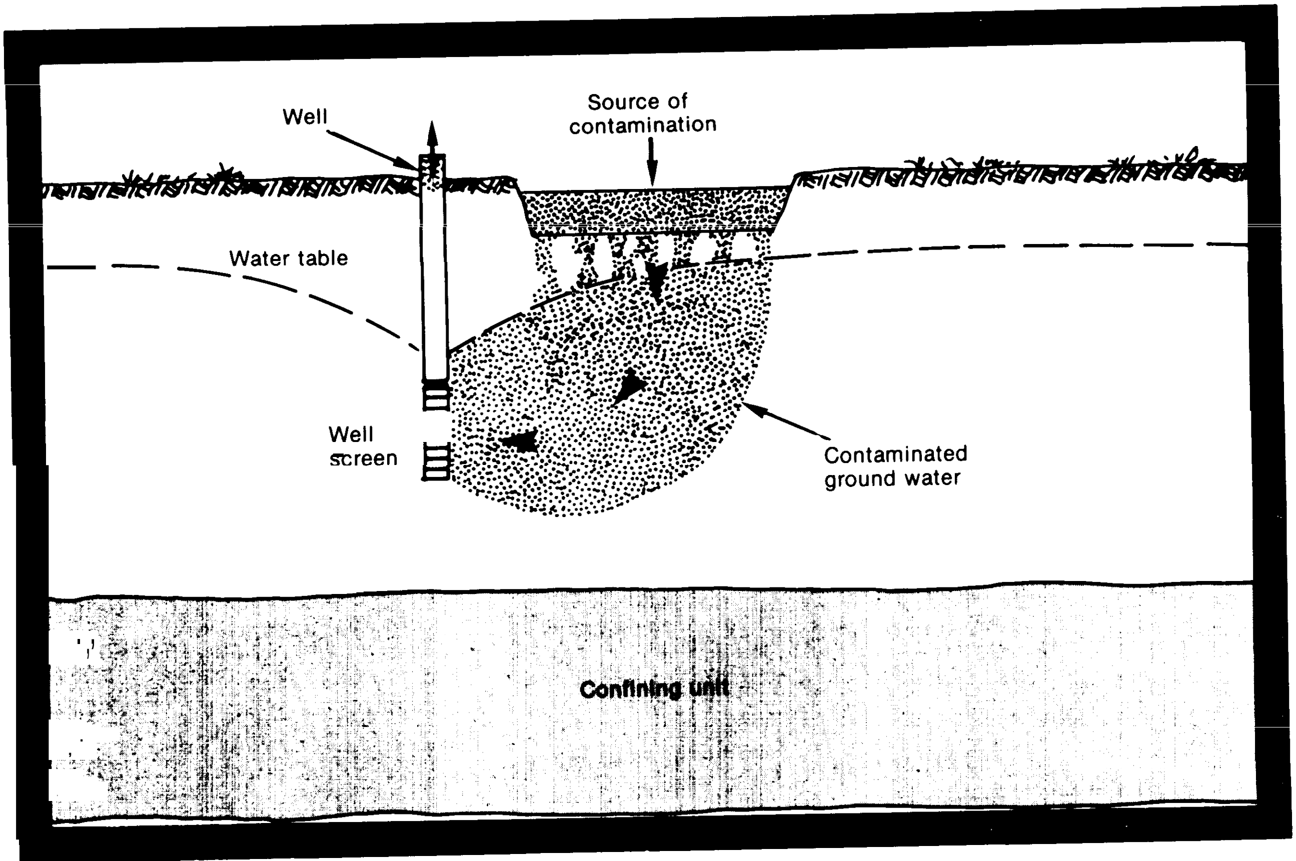
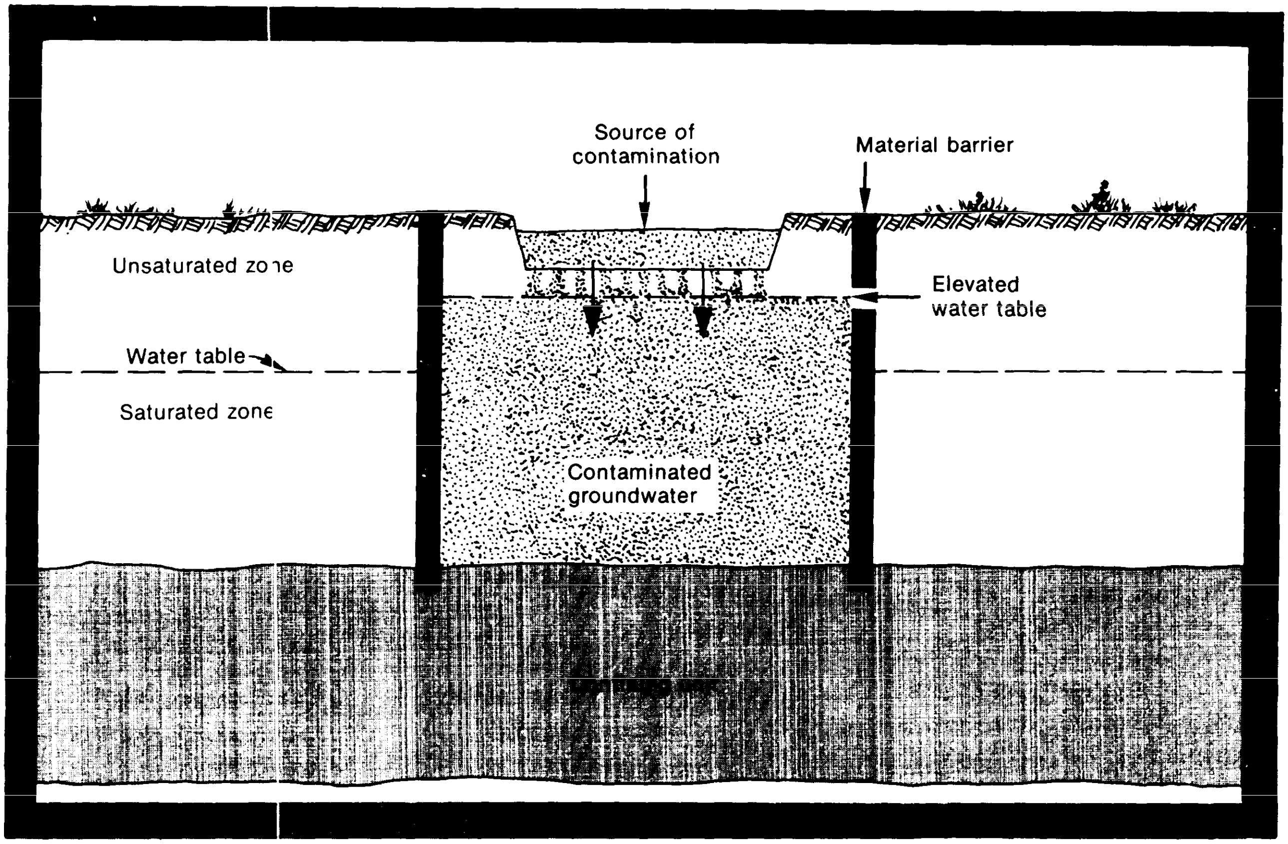


Photo cradt: Geraghb' & Miller, 198.3

Movement of contaminated groundwater can sometimes be controlled by pumping (i.e., hydrodynamic control) as shown above. Groundwater that is withdrawn must subsequently be treated and/or disposed of in some **way;** below, discharge lines carry recovered water away from the site.

Photo credit: Office of Technology Assessment



Credit: Geraghty & Miller, 198.3

Containment options that use material barriers depend on the presence of a horizontal stratum of low permeability and sufficient thickness for anchoring as shown above; some type of pumping scheme (e.g., wells or drains) may also be needed to prevent the overflow of contaminated water from inside the barrier. Backfill is being pushed into an almost completed slurry wall in the photograph below.

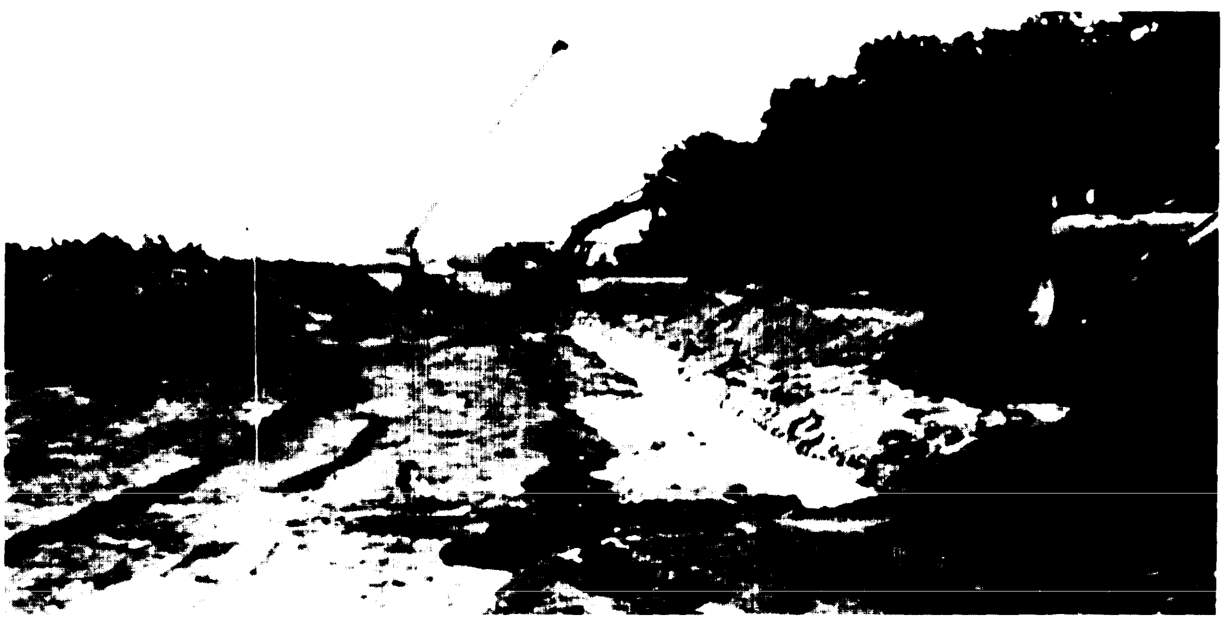


Photo credit: National Water Well Association

Photo credit: US. Environrnenta/ Protection Agency

Airstripping towers can be used to remove contaminants from groundwater; however, precautions must be taken to minimize any associated air pollution problems.

activities including pesticide and fertilizer applications).

Performance of Corrective Action Alternatives

Corrective actions have been taken to improve groundwater quality, but how well they perform remains uncertain over both the short and the long term. Inability to characterize performance of corrective measures arises because of the following five interrelated factors.

1) Performance is relative. Evaluation of performance requires the establishment of a benchmark or a target level for comparison. For example, when the desired reduction in contaminant concentrations is minor, many corrective action alternatives may qualify as "effective, but as the levels of desired or required cleanup increase, many alternatives may no longer qualify. Performance is also measured not only against existing conditions but in relation to future conditions—i.e., the suitability of improved quality to satisfy likely future uses.

2) Performance must be assessed in relation to the specific conditions at a given site (see the preceding section of this chapter). The site-specificity of groundwater contamination problems and, in turn, of the applicability of corrective action alternatives precludes a meaningful generalized assessment of technology performance.

3) Even when site information is available, there is always some degree of uncertainty about the subsurface environment —e.g., which substances are present, at what levels, and where (see ch. 5)—that can limit the effectiveness of alternatives in unforeseen ways. The principal uncertainty factors that influence performance are summarized in table 35 and relate to materials compatibility, the heterogeneity of the aquifer, and the types of substances present. Others are related to the qualifications of personnel and the quality of construction, handling, and operation.

4) There is virtually no long-term experience upon which to base the assessment of corrective actions. For example, although there have been federally funded cleanup activities under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and other Federal statutes, none has involved groundwater (see ch. 9). As a consequence, a then-ough performance evaluation of individual alternatives under different site conditions will not be available in the near term. Although many case histories are reported in the literature, they often do not contain enough detail for an evaluation of technology performance. In addition, access to information appears limited because it is often proprietary or involved in litigation.

5) The projected performance of technology and the degree of uncertainty about its performance depend on the time available to meet cleanup objectives or standards desired (e. g., as specified in permits, presented in a notice of regulatory compliance, and in response to public pressures) and on available funds. For example, in addition to specifying the levels to which the concentrations of substances must be reduced, a time frame may also be specified.[1] Time constraints may preclude many corrective act ion alternatives from consideration, perhaps resulting in a choice among more costly options; or desired cleanup standards may be neither technically nor economically feasible in the time specified.[2]

Although an accurate performance assessment is not presently possible, it is possible to reduce the uncertainties associated with performance and/or to improve the likelihood that an alternative will perform well. Examples are described below:

- The evaluation, selection, design, and implementation of corrective action alternatives are based on information obtained from hydrogeologic investigations. Thus, improving the reliability of hydrogeologic information (see ch. 5) will improve corrective action decision-making.
- Realistic expectations in terms of objectives, time, and costs are important in ensuring that failure is not inevitable.
- Monitoring can gauge long-term effectiveness and enable modification of the corrective actions chosen if necessary. But measuring performance is indirect and varies among the alternatives. Possible indicators of performance are presented in table 35.
- Quality control and quality assurance procedures—e.g., regarding the use of construction equipment on-site and the handling and placement of physical barriers—can also minimize the likelihood of poor performance.

Importantly, different types of uncertainties are associated with different alternatives, and the performance of some may be more certain (though *not* necessarily more desirable) than others, depending on site conditions. Management options are most often selected because their performance is the most certain. For example, terminating aquifer use depends neither on subsurface hydrogeology nor on the nature and behavior of substances; over the long term, however, there may be a risk of public exposure to substances remaining in the subsurface.

[1] In a surx'cy of rcmedial action projects undertaken for EPA (SCS Engineer-s, 1981), legal action to identify ' 'responsible" parties for correct i~'c action alone varied from 4 to 9 }'ears.

[2] For example, if cleanup stan+~ards must be achieved in, say, 5 years, then a time- and capital- inten: i~e method of containment may have to be chosen (e. g., a slurry wall requiring replacement once etery 50 years), precluding methods that have long-term operational requirements but smaller capital costs (c. g., hydrodynamic control). A net present value criterion would select hydrodynamic control in the abscncc of a near-term time constraint. However, a pumping system ma}' achie~e a 90-percent reduction in contain inant concentration levels in 5 years, but an additional 50 years may be required to reach a ~oal of 95-percent reduction.

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Table 35.—Corrective Action Techniques: Objectives, Performance, and Status

Technique	Objective	Principal components of uncertainty affecting performance	Measuring performance	Development status: Summary[a]	Development status: Remarks
Containment					
1. Slurry wall	To halt the horizontal migration of contaminants from a contamination plume; often used in conjunction with surface seal, run-on, and runoff controls.	• Long-term materials compatibility, particularly with certain organic solvents such as aromatics and halogenated species. • Wall consistency and integration with the confining bed. • Longevity of wall integrity. • Quality of design and installation.	Performance of a slurry wall is is determined by various methods. Monitoring well data outside of the wall can indicate the degree of leakage. Hydraulic head differences determine leakage potential; actual leakage can be calculated. Head measurements in underlying aquifers determine potential for vertical leakage. Permeability measurements of confining bed also determine leakage potential.	2	Technology for conventional, trenched slurry walls is well established as a construction dewatering practice; however, allowable leakage for construction applications is less critical than for contamination applications. In general, long-term (30 years) performance evaluations are not available because the operation requirements of dewatering are usually short term (less than 1 year). Historical records of long-term performance under exposure to varying contaminant types is also unavailable. Advanced techniques, such as the vibrating beam emplacement method, have a limited history of application to contamination problems and should be considered unproven.
2. Sheet pile	Same as slurry wall.	• Occurrence of premature pile failure, especially in the presence of highly concentrated corrosive contaminants.	Same as slurry wall except that measurements are taken at specific places where leakage is expected to occur, e.g., at pile joints and where piles are integrated with the confining bed.	2	This technique is conventionally used for construction dewatering. Its long-term viability in corrosive environments (e.g., acid wastes) is unproven. Also, the effectiveness with which the method can limit contaminant migration is questionable for stringent performance criteria (e.g., if low or no leakage is desired.)
3. Grouting	To encapsulate contaminants (via bottom and lateral grouting).	• Contact between the grout materials and all fracture and pore spaces. • Compatibility of formation fluids and wastes with grout materials.	Encapsulation processes cannot be easily monitored or controlled (e.g., a barrier wall can be more easily inspected during construction than injected grout; and grout injection is not as easily controlled as trenching). interpretation of monitoring well data for downgradient contaminants is the principal measure of performance.	2	Grouting is conventionally used in mine dewatering and dam construction. Design requirements in historical uses are generally to limit water flow, not to minimize or eliminate flow or to encapsulate contaminants.

Table 35.—Corrective Action Techniques: Objectives, Performance, and Status-continued

Technique	Objective	Principal components of uncertainty affecting performance	Measuring performance	Development status: Summary[a]	Development status: Remarks
4. Geomembrane	Same as slurry wall.	• Compatibility of synthetic membranes with organic solvents. • Installation of a vertical liner with grout backfill without damage. • Integration ot the liner with the confining bed.	Same as slurry wall.	3	Contamination applications are are in the R&D phase although the technology is commercially available. Field tests are only now being conducted; long-term performance data are not available.
5. Clay cutoff	To halt the horizontal migration of contaminants (in the unsaturated zone).	• Compatibility of materials and quality of installation.	Monitoring in the vicinity of the cutoff can be accomplished with suction lysimeters, core samples, and other techniques applicable to the unsaturated zone.	2	A clay cutoff is a standard construction technique but it has limited utility in groundwater contamination applications because horizontal migration in the unsaturated zone is most often negligible.
6. Liner	To limit the vertical migration of contaminants; commonly used as a facility design component.	• Occurrence of punctures due either to improper installation or to settling of underlying materials. • Impacts of organic solvents on synthetic liners or clays—e.g., holes or reduced effective permeability. • Quality of materials selection and installation.	Performance of liners can be monitored by underdrain collection systems or conventional monitoring well techniques.	1	Liner technology is well established and has been applied extensively to groundwater contamination problems. However, long-term performance data for both synthetic liners and compacted clays are limited. The use of underliners is limited mainly to hazardous-waste facility design.
7. Natural containment	To contain or otherwise limit the migration of contaminants via retardation in aqueous media, in geologic formations, or by hydrogeologic conditions.	• Representativeness of characterization of hydrogeology and contaminant retardation. • Accuracy and completeness of data, especially concerning contaminant retardation. • Heterogeneity of subsurface conditions.	Detection of contaminants in monitoring wells can verify predicted migration rates.	5,6	Techniques are available to predict the general direction and rate of movement of natural flow systems. But techniques used to predict contaminant migration rates and concentration levels (e.g., solute transport models) are not well established and subject to great uncertainty, particularly in the absence of supporting data.
8. Surface sealing	To limit infiltration into the contaminated area; commonly used in conjunction with runoff diversion ditches and material barriers (e.g., slurry wall and grouting) and with	• Quality of management, inspection, and repair.	Visual inspection can locate holes or cracks. Increased leachate production indicates leakage. Also, increased pumpage requirements in head management system may indicate leakage.	1	Conventional construction techniques are used to emplace surface seals. Effective infiltration control requires constant maintenance (e.g., due to the formation of stress cracks from settling or drying after dewatering).

Table 35.—Corrective Action Techniques: Objectives, Performance, and Status— continued

Technique	Objective	Principal components of uncertainty affecting performance	Measuring performance	Development status: Summary[a]	Development status: Remarks
	source isolation (e.g., to eliminate leachate production).				
9. Diversion ditches	To divert surface runoff away from the contaminated area.	• No major concerns.	Visual inspection is used to measure performance—e.g., during precipitation events.	1	This technique is a conventional construction method used for run-on/runoff control. It is often used in conjunction with surface seals.
10. Hydrodynamic control	To isolate contaminants via countering hydraulic gradients.	• Changes in local flow patterns due to modifications in existing pumping schemes or to installation of new pumping wells. • Downward flow which could allow contaminant migration into uncontrolled aquifers.	Water levels can be monitored in surrounding wells to observe gradients.	1,4	Techniques are not considered conventional or "on-the-shelf." Management of plumes and contaminant isolation in complex hydrogeologic settings require extensive engineering and testing. Long-term effectiveness is a function of constant fine-tuning to changes in head gradients. In dynamic flow systems (e.g., in systems modified by other pumping uses), pumping rates or patterns will require modification in real time.
Withdrawal					
1. Pumping	To limit the lateral migration of contaminants while gradually removing them from the aquifer matrix and formation fluids. (Source removal and/or isolation is also required to achieve ultimate reduction in contaminant concentrations.)	• The necessary length of time for operations. • Downward leakage of contaminants due to fracture systems, jointing, and abandoned wells.	Contaminant concentration levels can be measured in produced water to determine removal rates; and effects of pumping can be verified by monitoring water levels in surrounding wells. Underlying aquifers must be monitored to detect downward migration. Concentration levels after pumping is terminated must be monitored to determine increases in concentrations due to resorption. Geochemical interactions between contaminants and the aquifer matrix affect the partitioning of the contaminant between solid and water phases; the potential effectiveness and length of operations are dependent on these interactions.	1	Pumping techniques (e.g., wells) are used conventionally for water supply development and more recently for plume management. Techniques are reliable and performance can be verified. Numerous applications to groundwater contamination are in place, and performance data are available.

Table 35.—Corrective Action Techniques: Objectives, Performance, and Status—continued

Technique	Objective	Principal components of" uncertainty affecting performance	Measuring performance	Development status: Summary[a]	Development status: Remarks
2. Gravity drainage	Same as pumping.	same as pumping.	Same as pumping.	1	A type of fluid recovery technology, this method is used extensively in dewatering activities and for groundwater contamination. It is a reliable, simple technique which is applicable in many surficial, unconsolidated formations. Performance data are available.
3. Withdrawal enhancement	To enhance contaminant removal efficiencies via the the injection of chemicals, steam, or other additives.	Ž Lack of proven effectiveness of technology. • Introduction of additional contaminants to the aquifer (e.g., chemical reagents and their byproducts). • Introduction of volatiles to the atmosphere (e.g., via the use of steaming in surficial applications). . Presence of inorganic substances (i.e., use is limited to organic constituents).	Same as pumping.	2,3,4[b]	This technique is not conventionally applied to groundwater contamination problems. Steam or heat injection, although used in confined formations in oil field applications, have not been extensively tested in surficial contamination problems where concentrations of organics are much lower and objectives for removal are more stringent (50% recovery of oil in place is often considered reasonable). Surfactant injection is still considered an advanced technique in enhanced oil recovery operations, and injectants are often considered hazardous.
4. Gas venting	To remove volatile contaminants from the subsurface.	• Lack of proven effectiveness in complex media.	Measurements can be taken using gas collection probes.	1	Gas venting is conventionally used in landfill design and operation. Vapor extraction in the unsaturated zone appears capable of removing the soluble fraction of volatile compounds from the saturated zone.
5. Excavation	To remove contaminated water and/or soil materials.	Ž Increased contaminant migration (e.g., via breaking of drums or additional infiltration during precipitation). • Availability of secure disposal **areas** for excavated contaminants. • Extent of contamination and resulting costs.	Contaminant concentration levels can be measured in surrounding soil and aquifer materials and in surrounding waters to verify total removal. Measurements are most accurate if contaminants are highly concentrated and limited in depth and volume.	2	Direct excavation is a conventional technology. However, associated health and safety measures are continually under development and are likely to increase costs substantial y.

Table 35.—Corrective Action Techniques: Objectives, Performance, and Status—continued

Technique	Objective	Principal components of uncertainty affecting performance	Measuring performance	Development status: Summary[a]	Development status: Remarks
		• Uncertainty Increases it contaminants are neither highly concentrated nor limited in depth or volume.			
Treatment	In general, to transform (thereby removing) contaminants via physical, chemical, or biological means.	• Occurrence of shock loadings. • Nature, mix, and concentration of contaminants; uncertainty increases if contaminants are not highly concentrated. • Equipment design and operation (e.g., membrane maintenance for filtration, ultrafiltration, and electrodialysis; and proper controls for providing reagents for adsorption and chemical transformation). • Subsurface hydrogeology to the extent that contaminated groundwater is to be withdrawn from the aquifer.	In general, influent and effluent can be monitored for contaminants.	1[c]	Treatment techniques are generally "on-the-shelf" and with basic engineering can be adapted to many groundwater contamination incidences. However, management of treatment systems for multiple contaminants and for rapidly changing concentrations may prove to be difficult. Performance data are not available for groundwater contamination applications using ultrafiltration, reverse osmosis, steam stripping, ion exchange, and electrodialysis.
In-situ rehabilitation					
1. Biological degradation	To degrade contaminants via the injection of micro-organisms into the subsurface or by stimulating the growth of in-situ bacteria.	• Contact between the reagents and the entire contamination mass, particularly in heterogeneous aquifers. • Predicting the behavior of micro-organisms. • Tailoring micro-organisms to contaminants. • Performance is highly uncertain.	Contaminant levels can be monitored in soil and water.	4,5	Techniques are in the R&D stage with minimal commercial application. They have a potentially limited application to groundwater due to practical constraints such as the volume of organisms required, reaction kinetics, and the assimilative capacity of organisms for certain contaminants. In heterogeneous formations, access to the entire contaminant mass may be practically impossible. Techniques are most often applied to petroleum-related spills.
2. Chemical degradation	To degrade or immobilize contaminants via the injection of chemicals into the subsurface.	• Contact between the reagents and the entire contamination mass, particularly in heterogeneous aquifers. • Performance is highly uncertain.	Same as biological degradation.	4,5	Techniques are in the R&D stage with minimal commercial application. They have a potentially limited application to groundwater due to practical constraints including reaction kinetics and reactivity of contami-

Table 35.—Corrective Action Techniques: Objectives, Performance, and *Status-continued*

Technique	Objective	Principal components of uncertainty affecting performance	Measuring performance	Development status	
				Summary[a]	Remarks
					nants. In heterogeneous formations, access to the entire contaminant mass may be practicably impossible.
3. Water table adjustment	To allow for the aerobe degradation of contaminants by lowering the water table.	• Potential for aerobic degradation is limited to certain organic contaminants. • Prediction of degradation rates or processes,	Contaminant concentrations can be monitored in soil and water. Underlying saturated media can be monitored to determine contaminant levels.	4,5	The methods of pumping and gravity drainage used to alter water table levels are well established. Evaluation of the impacts of such adjustments on contaminant degradation, however, is not well defined or established, and the technique is not conventionally applied in plume management. Source isolation is a possible application. Raising the water table can provide flushing benefits in some cases.
4. Natural process restoration	To allow for the degradation and dispersion of contaminants in the natural flow system.	• Prediction of contaminant migration behavior; heterogeneities in aquifer conditions reduce accuracy of predictions. • The presence of non-degradable contaminants that, although highly retarded, continue to migrate at low velocities.	Downgradient levels of contaminants in soil and water can be measured.	5,6	Methods used to predict concentration reductions (e.g., solute transport models) are not highly reliable. Monitoring the actual attenuation of contaminants is a conventional practice and performance can be monitored.
Management options					
1. Limit/terminate aquifer use	To minimize the exposure of possible users to contaminated groundwater.	• The ability to shut down domestic wells due to possible public resistance. • The ability to enforce usage patterns in cases of environmental exposure (e.g., to sport fish or streams).	Exposure levels can be monitored; actual use patterns over time can be determined. Performance is also economic—e.g., it may be cheaper to terminate use and import water or develop alternative supplies than to treat supplies or otherwise correct contamination.	6	Historically this is a common response to aquifer contamination.
2. Develop alternative water supply	To provide a substitute water supply by developing alternative water sources.	• Availability of water supply alternatives, especially in water-short areas which may, in turn, limit the long-term growth of an area.	Performance is mainly economic —e.g., it may be cheaper to terminate use and develop alternative supplies or import water than to treat supplies or otherwise correct contamination.	6	In conjunction with limiting/terminating aquifer use, alternative water supply development is a frequently implemented response.

Table 35.—Corrective Action Techniques: Objectives, Performance, and Status—continued

Technique	Objective	Principal components of uncertainty affecting performance	Measuring performance	Development status: Summary[a]	Development status: Remarks
3. Purchase alternative water supply	To provide a substitute water supply through importation or other purchases.	• Reliance on imports, especially in water-short areas where the supply may be terminated or depleted. • Potential opposition to inter-basin transfers.	Performance is mainly economic—e.g., it may be cheaper to terminate use and develop alternative supplies or import water than to treat supplies or otherwise correct contaminant ion.	6	This is a frequently implemented response although generally considered a short-term solution.
4. Source removal	To remove physically the source of contaminant ion.	• Increased contaminant migration (e.g., via breaking of drums or additional infiltration during precipitation). • Availability of secure disposal options. • Extent of contamination and resulting costs. (See Excavation, above.)	Contaminant concentration levels can be measured in surrounding soils, aquifer materials, and waters to verify total removal.	1	Conventional construction techniques are used for source removal although substantial increases in health and safety precautions are required for groundwater contamination applications. Current activity already involves significant health and safety measures.
5. Monitoring	To delineate and track the migration (and concentrations) of contaminants.	• Undetected plume migration because of improper placement or sampling of wells. • Mistakes are difficult to detec until a problem occurs or backup wells around key exposure points are installed.	Performance can be measured by duplicating samples and analyses. Use of qualified personnel are essential for proper well placement and for the overall groundwater quality investigation.	1,6	Conventional technology is used for monitoring groundwater contamination problems and conducting hydrogeologic investigations. If methods are used properly, reliable plume delineation and migration data can be generated (see also ch. 5).
6. Health advisories	To limit the use of contaminated groundwater by advising users of contamination.	. The ability to enforce usage patterns in cases of environmental exposure (e.g., to sport fish or streams). The ability to shut down domestic wells due to possible public resistance.	Exposure levels can be monitored; actual use pattern over time can be determined. Performance is also economic—e.g., it may be cheaper to terminate use and develop alternative supplies or import water than to treat supplies or otherwise correct contamination.	6	This option is a conventional practice of State and local health departments.
7. Accept increased risk	No action taken.	• The ability to predict contaminant migration. • Corrective action alternatives can be more expensive as the contaminant spreads out (i.e., a larger plume).	Performance is often measured in economic terms.	6	Historically this option is the response to many contamination incidence. Impacts on population are unclear.

[a]Key: 1—Technology is proven; performance data are available from applications to groundwater contamination problems.
2—Technology is proven In applications other than groundwater contamination; long-term performance data are unavailable for groundwater contamination.
3—Technology is In R&D stage with respect to groundwater contamination applications, although proven for other applications; performance is generally unknown for groundwater contamination problems.
4—Application of technology has been limited to specific, narrowly def!ned site conditions.
5—Technology is generally in R&D stage; results are unreliable.
6—Technology has been applied historically —e.g., before the development of regulatory programs and consideration *of* potential long-term impacts.
bwlthdrawal enhancement techniques that would be a "5" include surfactant injection.
cTreatment technologies that would be ,,2,, are ultrafiltration, r@v@rs@ osmosis, steam strlpplng, ion exchange, and elect rodlalysis.

SOURCE: Office of Technology Assessment.

STAGE OF DEVELOPMENT OF CORRECTIVE ACTION ALTERNATIVES

The development status of alternatives is also summarized in table 35. Generally, alternatives for corrective action are commercially available. However, they have usually been developed for industrial and surface water uses, which do not require the level of reduction, removal, and/or control of substances that is necessary for groundwater contamination problems. For example:

- containment methods were developed in the construction industry for dewatering, foundation, and embankment applications;
- withdrawal methods were developed for groundwater supply (i.e. , quantity) development and for petroleum recovery;
- treatment methods were developed for wastewater (i. e., surface water) and desalination applications; and
- management options have generally been applied in the areas of wastewater (i. e., surface water) treatment and water supply (i. e., quantity) development.

Some commercial alternatives require only minor modifications, if any, for groundwater contamination purposes. These alternatives include some management options (e. g., the development of alternative supplies) and, to a lesser extent, excavation if precautions are taken with respect to materials handling and disposal.

Other commercial alternatives require continued research and development before they can be applied effectively to contaminated groundwater. For example, containment needs relate principally to the permanence of installation—e. g., materials compatibility, field validation procedures, quality control, and leak detection (EPA, et al., 1983). With respect to treatment, research and development is needed for radionuclides; viruses; certain organic chemicals, including halogenated compounds; and complex mixtures of substances. Research also needs to continue on modifying existing wastewater treatment facilities to handle a broader spectrum of substances than they typically handle. In general, the technologies for treating substances in groundwater are likely to differ substantially from those developed for contaminated surface water and wastewater because of the marked differences among the types and concentrations of substances present.

Some innovative methods are being developed specifically for application to groundwater contamination problems. For example, research and development for in-situ rehabilitation originated in the context of petroleum spills, and withdrawal enhancement techniques are being developed in the context of hydrodynamic control. Because innovative methods tend to be substance-specific, they are likely to be useful only on a limited scale in the long term.

Although some available technology and likely developments appear promising for specific types of contamination problems, technology alone cannot be expected to correct the full range of problems likely to be encountered. It will take years, or even decades, of testing and monitoring to develop reliable performance data. Even then, the knowledge gained will be site-specific.

CHAPTER 8 REFERENCES

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