

Site Remediation Technologies: A Reference Manual

Contaminated Sites Management Working Group

By:
Water Technology International Corp., Burlington, Ontario
March 1997

This document has been reviewed by the members of the federal interdepartmental Contaminated Sites Management Working Group (CSMWG), and approved for publication. Any reference to trade names or commercial products does not constitute recommendation or endorsement for use

For a copy of this report, contact:
Environment Canada
Hazardous Waste Branch
Place Vincent Massey
351 St. Joseph Blvd., 12th Floor
Hull, Quebec K1A 0H3
Telephone: (819) 953-0458

Ce rapport est aussi disponible en français sous le titre:
Les technologies d'assainissement des lieux contaminés : manuel de référence

**Site Remediation Technologies:
A Reference Manual**

TABLE OF CONTENTS	PAGE
Introduction	i
Chapter 1: Remediation Strategies	1
1.1 Types of Sites and Contamination.....	1
1.2 General Remediation Strategies.....	6
1.3 Decision Making Strategies	6
Chapter 2: In-situ Treatment of Soil and Groundwater	9
2.1 Overview	9
2.1.1 Advantages of In-situ Treatment.....	9
2.1.2 Disadvantages of In-situ Treatment	10
2.2 Types of In-situ Remediation Technologies.....	10
2.3 Soil Remediation in the Unsaturated Zone	11
2.3.1 Soil Vacuum Extraction.....	12
2.3.2 Bioremediation.....	12
<i>Bioventing</i>	13
<i>Bioslurping</i>	13
<i>Land Treatment</i>	13
2.3.3 Soil Flushing	14
2.3.4 Thermal Treatment	15
<i>Volatilization</i>	15
<i>Solidification</i>	16
2.3.5 Electrokinetics.....	16
2.3.6 Phytoremediation.....	17
2.3.7 Natural Attenuation	17
2.3.8. Delivery/Recovery Systems	18
<i>Soil Mixing</i>	18
<i>Pneumatic/Hydraulic Fracturing</i>	18
2.3.9 Technologies Frequently Used to Remediate the Unsaturated Zone	18
2.3.10 Summary and Comparison of Technologies for the Unsaturated Zone	20
2.3.11 Treatment Costs	20
2.4 Soil and Groundwater Remediation in the Saturated Zone	20
2.4.1 Pumping of Free Product.....	21
2.4.2 Bioslurping	22
2.4.3 Groundwater Pump and Treat Systems	22
2.4.4 Insitu Bioremediation	24
<i>Pump and Reinject</i>	24
<i>Air Sparging</i>	25
2.4.5 Treatment Walls	26
2.4.6 Natural Attenuation	27
2.4.7 Technologies Frequently Used to Remediate the Saturated Zone	27
2.5 Summary.....	27

Chapter 3: Treatment of Extracted Groundwater.....	29
3.1 Overview	29
3.1.1 Comparison of In-situ and Ex-situ Technologies for Groundwater Remediation...	29
3.1.2 Situations Favouring Ex-situ Treatment of Contaminated Groundwater	30
3.1.3 Constituents to be Removed from Extracted Groundwater	31
3.2 Types of Ex-situ Groundwater Remediation Technologies	31
3.3 Free Product Recovery.....	32
3.4 Groundwater Pre-treatment.....	34
3.5 Groundwater Treatment for Dissolved Organic Contaminants.....	34
3.5.1 Air Stripping	34
3.5.2 Steam stripping.....	35
3.5.3 Advanced Oxidation.....	35
3.5.4 Carbon Adsorption (Liquid Phase)	36
3.5.5 Bioreactors	37
3.5.6 Membrane Separation	38
3.5.7 Technologies Commonly Used to Remove Organic Contaminants from Extracted Groundwater.....	39
3.6 Groundwater Treatment of Dissolved Inorganic Contaminants.....	39
3.6.1 Oxidation/Reduction.....	39
3.6.2 Adsorption	40
3.6.3 Membrane Separation	40
3.6.4 Ion Exchange.....	41
3.6.5 Precipitation	42
3.6.6 Coagulation/Flocculation.....	42
3.6.7 Filtration.....	43
3.6.8 Technologies Commonly Used to Remove Inorganic Contaminants from Extracted Groundwater.....	43
3.7 Summary.....	44
 Chapter 4: Off-gas Treatment.....	 45
4.1 Overview	45
4.2 Off-gas Treatment Technologies.....	47
4.2.1 Dust Removal technologies	48
4.2.2 Carbon Adsorption.....	48
4.2.3 Condensation.....	48
4.2.4 Incineration	49
4.2.5 Flares.....	49
4.2.6 Catalytic Oxidation	49
4.2.7 Thermal Reduction	50
4.2.8 Photo-oxidation.....	50
4.2.9 Biofilters.....	50
4.2.10 Off-gas Recycle	51
4.3 Considerations in the Use of Off-gas Treatment	51
4.4 Summary.....	53

Chapter 5: In-situ Containment of Soil and Groundwater	55
5.1 Overview	55
5.2 Hydraulic Containment Techniques	56
5.2.1 Pumping	56
5.2.2 Cut-off Trenches and Drains.....	58
5.3 Physical Containment Techniques	59
5.3.1 Slurry Walls	59
5.3.2 Grout Curtains	59
5.3.3 Sheet Pile Walls	60
5.3.4 Surface Caps.....	61
5.4 Considerations When Planning to Use a Containment System	62
5.5 Summary.....	62
Chapter 6: Ex-situ Treatment of Excavated Material	65
6.1 Overview	65
6.2 Disposal Options	67
6.2.1 Hazardous Waste Disposal.....	67
6.2.2 Industrial or Municipal Waste Disposal (Landfill).....	67
6.2.3 On-site Disposal/Containment	67
6.2.4 Aquatic Disposal	68
6.2.5 Storage	68
6.2.6 Re-use/Recycle	68
6.2.7 Fill.....	68
6.2.8 Considerations in the Use of Ex-situ Treatment.....	69
6.3 Treatment Options.....	70
6.3.1 General Remarks.....	70
6.4 Treatment Technology Classes	73
6.4.1 Pre-treatment.....	73
6.4.2 Biological	75
6.4.3 Chemical.....	76
6.4.4 Metal Extraction	77
6.4.5 Thermal	78
6.4.6 Immobilization by Fixation or Solidification.....	79
6.5 Cost Considerations of Treatment Technologies.....	80
6.6 Summary.....	83
Chapter 7: Monitoring	85
7.1 Project Monitoring	86
7.2 Post-project or Long-term Monitoring	87
7.3 Summary.....	90
References	91
Suggested Reading.....	93

Appendix A: Glossary

Appendix B: Case Studies

Gloucester Landfill Pump and Treat (Ontario)
Plume Control and In-situ Remediation, CFB Borden (Ontario)
Ex-situ Bioremediation of Heavy Hydrocarbons, CFB Trenton (Ontario)
Remediation of the Firefighter Training Site, Sept-Iles Airport (Québec)
Rigaud Pump and Treat (Québec)
Soil Washing of Hydrocarbon Contaminated Soil, Ste-Anne-des-Plaines (Québec)
Ex-situ and In-situ Bioremediation of Coast Guard Sites, Newfoundland
Hamilton Harbour Sediment Ex-situ Bioremediation (Ontario)
Ex-situ Bioremediation of Hydrocarbon Contaminated Soil, Lyell Island (B.C.)

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

INTRODUCTION

Background

This manual has been prepared for the Contaminated Sites Management Working Group (CSMWG) which is an interdepartmental committee of the federal government established to investigate and promote a common approach to the management of federal contaminated sites. In 1996, the CSMWG sponsored a series of three (3) day workshops titled "Workshops on the Management of Federal Contaminated Sites" which were delivered to employees of federal departments involved in site remediation.

Five (5) workshops were delivered, one in each of the geographic regions of Canada. This manual is based on the Remediation Technologies section of the workshop which was developed and delivered by Water Technology International and contains all of the material presented at all of the workshops. The basic presentation at each workshop remained the same but the presentations were modified slightly over time, based on the feedback received by participants. The workshops were also supplemented with Case Studies which changed from location to location.

The manual is intended to be a general reference for federal employees involved with site remediation work. It is written to enable newcomers to the field to understand the concepts discussed. Most statements in the text are not referenced. The concepts presented in this manual are those formed by the authors based on years of work in this field. Most of the concepts are not new but come out of the shared experience of consultants and regulators in this field. Any figures, diagrams or quotations are referenced to the original author.

Objectives of the Workshops and this Manual

The purpose of the technical workshops was to give a general overview of the various types of remedial strategies and technologies available in Canada and to promote technology based solutions to site remediation problems. This manual is intended to be a general reference manual and for those wishing more detail, general texts and texts devoted to specific subjects are available. Some useful references and suggested reading are provided at the end of this manual.

The workshops were also a forum for the exchange of ideas and information between participants. Some of the ideas arising from the workshops have been incorporated into this manual.

Water Technology International Corp.

Water Technology International Corp. (WTI) is an employee-owned company which has a contract to operate Canada's Wastewater Technology Centre (WTC) in Burlington, Ontario. The WTC has been privately operated since 1991 and provides research and development, laboratory and consulting services to government and industry.

WTI's Site Remediation Division provides site assessment, site remediation and technology assessment services as well as conducting research and development (R&D). Some recent R&D projects have focused on advanced ultraviolet destruction systems, specialized bioventing, bioslurry treatment of soils and sediments and surfactant washing of PCBs. WTI has also operated the Gloucester, Ontario groundwater treatment plant for four years and completed technical audits of 55 remediation projects funded under the former National Contaminated Sites Remediation Program (NCSRP). Under the Development and Demonstration of Site Remediation Technologies (DESRT) program, WTI developed the Site Remediation Treatment Technology (REMTEC) Database which contains information on over 500 technologies.

The Authors

The WTI staff who prepared and presented the workshop material and wrote this manual are:

- Alex Lye, Msc
Head - Groundwater Applications
- Ralph Ludwig, PhD
Head - Subsurface Applications
- Craig Wardlaw
Head, Soils and Sediments

Acknowledgments

WTI would like to thank the Contaminated Sites Management Working Group and Environment Canada for funding this work as well as Dave Hay, Manager of the Burlington Environmental Technology Office (BETO) and Gord Owen, Chief of the Prevention and Treatment Division of Environment Canada for their assistance in the contractual arrangements and the promotion of the workshops.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 1: REMEDIATION STRATEGIES

This chapter is intended to give a brief overview of the strategies available for remediating contaminated sites. Also provided are some explanations on the basics of decision-making for site remediation projects. For a more in-depth discussion of these topics the reader should consult further sources, some of which are listed in the References section located at the end of this manual.

“Site remediation” is a general term which has different meanings to different people. The most general definition of “site remediation” is the cleaning up of contaminants in either a solid matrix (mainly soil) or in groundwater. In some cases however there is no clean-up at all, rather the contaminants are contained or immobilized. Therefore the word “remediation” should be seen as having broader meaning than “cleanup”.

For example, the CCME’s proposed definition states that “Remediation involves the development and application of a planned approach that removes, destroys, contains or otherwise reduces availability of contaminants to receptors of concern (CCME Guidance Document on the Management of Contaminated Sites - Draft - January, 1996).

The term “site” also needs definition since there are numerous ways to define a site. This term is better explained in the next section, while Appendix A contains a list of other common terms and their definitions.

1.1 Types of Sites and Contamination

“Sites” in the context of site remediation have no one definition but rather are characterized more by the type of human activity which caused contamination to occur. Sites can be very large (several hundred hectares) or very small (10 square meters). Contaminated sites can be comprised of contaminated soil, contaminated groundwater (which can have a larger area than the property boundary), pure liquid or solid chemical products on the ground surface or below the ground surface, vapours in the pore spaces of the soil, contaminated sediment, sludges and many more types of substances. In general, every site is slightly different. This is what makes the field of site remediation very interesting to study but very difficult to “package”. Each site remediation project is different and has a unique solution.

One simple distinction needs to be made to avoid confusion. For the purposes of this discussion a “contaminated site” is a distinct area or volume of space which was contaminated by one type of activity. This definition separates a contaminated site from a “contaminated facility”. A facility is usually a piece of property with legally defined boundaries which may have one or several contaminated sites present either within its boundaries or partially within its boundaries. This document does not deal with facilities management but rather the techniques for dealing with each contaminated location.

Contamination of sites can be caused by one or more of the following incidents:

- leakage of storage or disposal sites;
- spills;
- legal or illegal disposal of substances directly into the environment;
- build-up of contaminants from point or non-point discharges;
- inadvertent release of contaminants from industrial or commercial activities; and
- abandonment of buildings or properties.

The types of contaminants are usually categorized as follows:

1. **Oxygen-depleting organics** (eg. animal manure, human waste, plant by-products) and **nutrients**, such as potassium, phosphate and nitrogen (P,K,N)) - the impacts of these substances are oxygen depletion, excessive algae and bacterial growth and growth of pathogenic organisms.
2. **“Toxic” organics** (eg. Polychlorinated biphenyls (PCBs), petroleum hydrocarbons, pesticides (DDT), creosote) - these substances have lethal, carcinogenic, teratogenic, mutagenic, immuno-depressing or other health effects on humans or other life forms.
3. **Metals** (eg. zinc, cadmium, lead, mercury) - these are primary elements or compounds of these elements which have lethal, carcinogenic, teratogenic, mutagenic, immuno-depressing or other health effects on humans or other life forms.
4. **Radioactives** (eg. uranium, heavy water, radon gas, cesium) - these are also primary elements with lethal, carcinogenic, teratogenic, mutagenic, immuno-depressing or other health effects on humans or other life forms but have the additional property of emitting energy in the form of waves or “rays” (X, beta, gamma).
5. **Nuisance substances** (eg. sulphur, iron, methane, sodium, calcium carbonate or calcite (CaCO₃) suspended solids, unexploded ordinance) - these substances cause taste problems in water, odours, explosion hazards, fouling problems in pipes and treatment systems.

In this document all of the above types of substances are discussed except for radioactives. The handling of radioactives requires special training and, since radioactive contamination is relatively rare in Canada, most remediation project managers may never encounter a radioactive site.

The following is a list of typical contaminated sites:

- Unregulated former disposal sites;
- Industrial properties - spills, leaks, open storage areas, fill areas;
- Electrical facilities - PCB leaks and spills;
- Fire-fighter training areas;
- Ports and waterways where past industrial discharges contaminated sediment;
- Lagoons used to store or “treat” industrial effluents;
- Mine tailings ponds;
- Above and below ground fuel storage sites;
- Industrial storage or transportation sites;

- Municipal and industrial landfills;
- Military training areas;
- Sites with hazardous building materials (asbestos, leaded paint, PCB light ballasts);
- Abandoned buildings with inventory of fuel, chemicals, products, etc.;
- Transportation routes where spills or spraying of oil or chemicals have occurred;
- Sites of major fires (St-Basille, Hagersville); and
- Wood preserving sites

Another way to look at the types of contaminated sites is their level of “maturity” or “state of progression”. Since contaminants and the forces of nature are dynamic (ie. contaminants tend to move through the environment) contaminated sites can have very different characteristics depending on the time frame of the contamination and the speed at which dispersion and advection have occurred. Figures 1.1 through 1.4 illustrate the typical progression of a site from uncontaminated to “fully” contaminated for both a “light non-aqueous phase liquid” (LNAPL) and a dense non-aqueous phase liquid” (DNAPL).

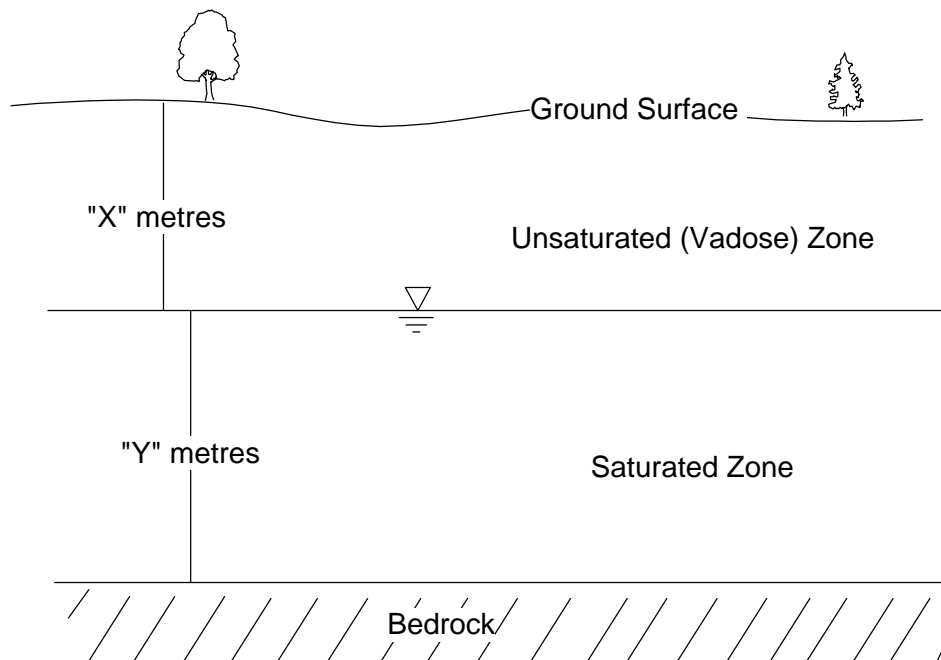


Figure 1.1 Subsurface situation at a typical industrial property before contamination.

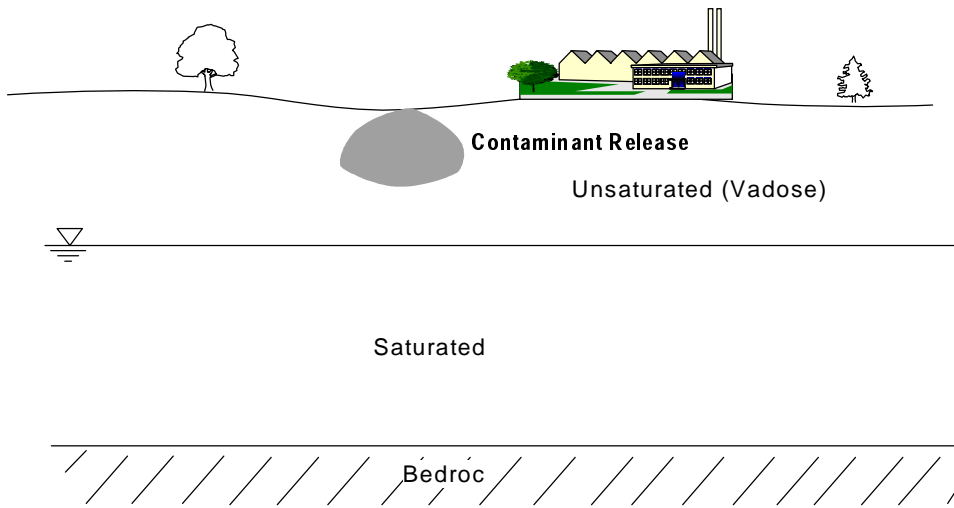


Figure 1.2 Typical subsurface contamination immediately after release of contaminant. Contamination is only in the soil located in the vadose zone.

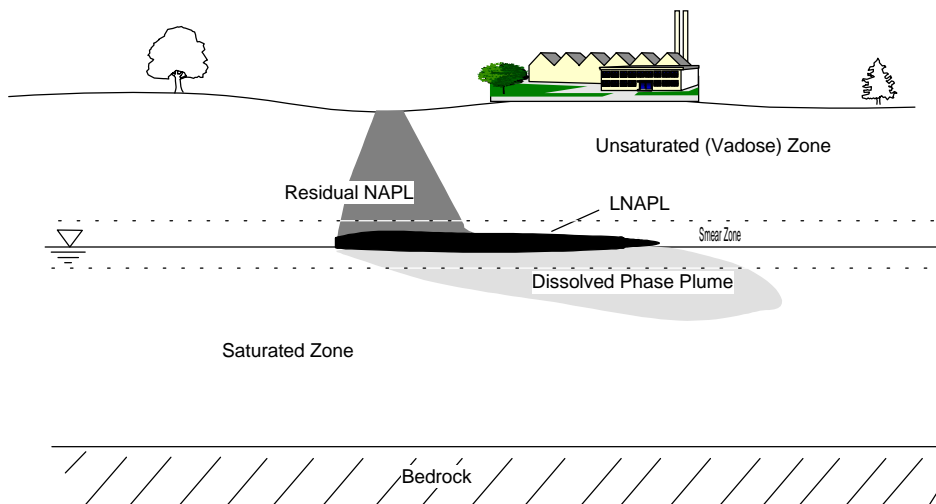


Figure 1.3 Typical "mature" contamination scenario where contaminant is a light non-aqueous phase liquid (LNAPL).

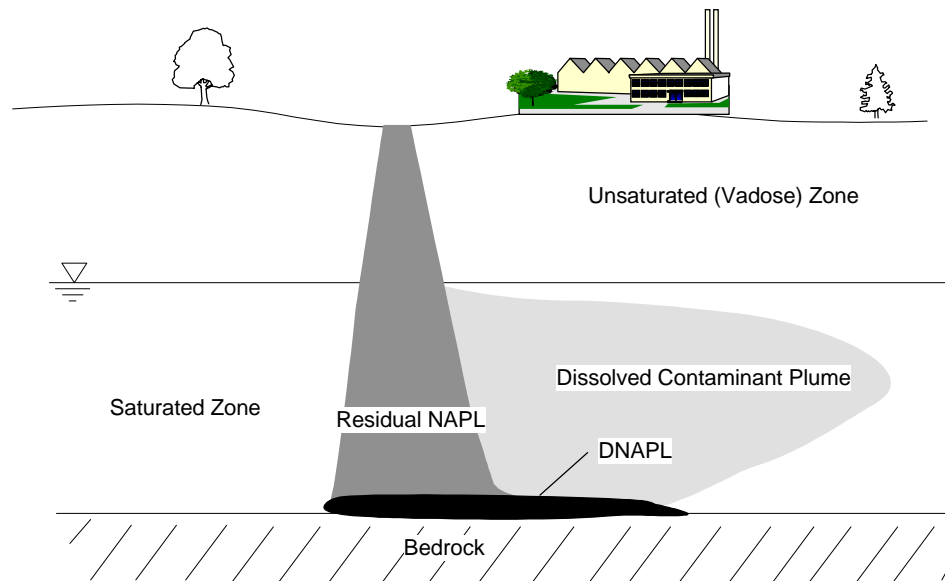


Figure 1.4 Typical “mature” contamination scenario where contaminant is a dense non-aqueous phase liquid (DNAPL).

Figure 1.2 illustrates the simplest type of contamination where the liquid contaminant has stained the soil in the unsaturated zone but has not reached the water table (saturated zone). Figure 1.3 and 1.4 illustrate fully developed contamination scenarios involving contamination of all compartments of the subsurface environment. The soil in both the unsaturated and saturated zone is stained or “smeared” with contaminant, there is “free product” occupying the pore spaces of the soil and there is dissolved contaminant in the groundwater (a “plume”). The difference between LNAPL and DNAPL sites is that the LNAPL progresses downwards in the unsaturated zone until it reaches the water table and then floats on the water while the DNAPL continues downwards through the groundwater until it reaches an impermeable layer such as bedrock or a clay layer. The scenarios could get worse still if the contaminant was to enter fractures in the bedrock.

There are numerous other contamination scenarios besides the ones shown in Figures 1.2 to 1.4. One other common scenario in Canada is a site with bedrock close to or at the ground surface. The water table in this case is below the surface of the bedrock therefore there is no saturated soil zone. These sites tend to be easier to remediate than sites with a deep overburden (unless liquid contaminant has seeped into fractures in the bedrock in which case remediation will be very difficult).

Another common contamination scenario in Canada is contaminated sediment. All of the same remediation options apply to sediment as to soil but the specific remedial techniques can be quite different.

1.2 General Remediation Strategies

There are a relatively small number of general options but a very large number of specific techniques for remediating contaminated sites. The general remediation options are shown in Figure 1.5. The rest of this document is organized according to these general options, that is:

Chapter 2: In-situ Remediation of Soil and Groundwater

Chapter 3: Pump and Treatment of Groundwater

Chapter 4: Off-gas Treatment

Chapter 5: In-situ Containment

Chapter 6: Ex-situ Remediation of Excavated Materials

1.3 Decision-Making Strategies

In general, the most poorly planned part of site remediation projects is the decision-making strategy. The reasons for this are numerous but the main ones are that decision-making is not ranked as a high priority task by most project planning teams and that decision-making methods are poorly understood in general. Most project managers and planning teams tend to focus primarily on the choice of specific technology instead of on all of the general options for remediating the site. Many projects involve no decision-making at all because the remedial alternative has been pre-determined by either the site owner or the general contractor.

There are numerous acceptable methods for making decisions. After a site assessment has been completed, we recommend a three step process:

- **Step I: Set Cleanup Goals and Criteria**
 - Ensure that the site contamination is completely characterized
 - Determine regulatory requirements and criteria and involve appropriate government regulators and approval personnel in the planning
 - Determine technical, spatial and temporal restrictions
 - Determine the overall goal of the project and the site- specific cleanup criteria

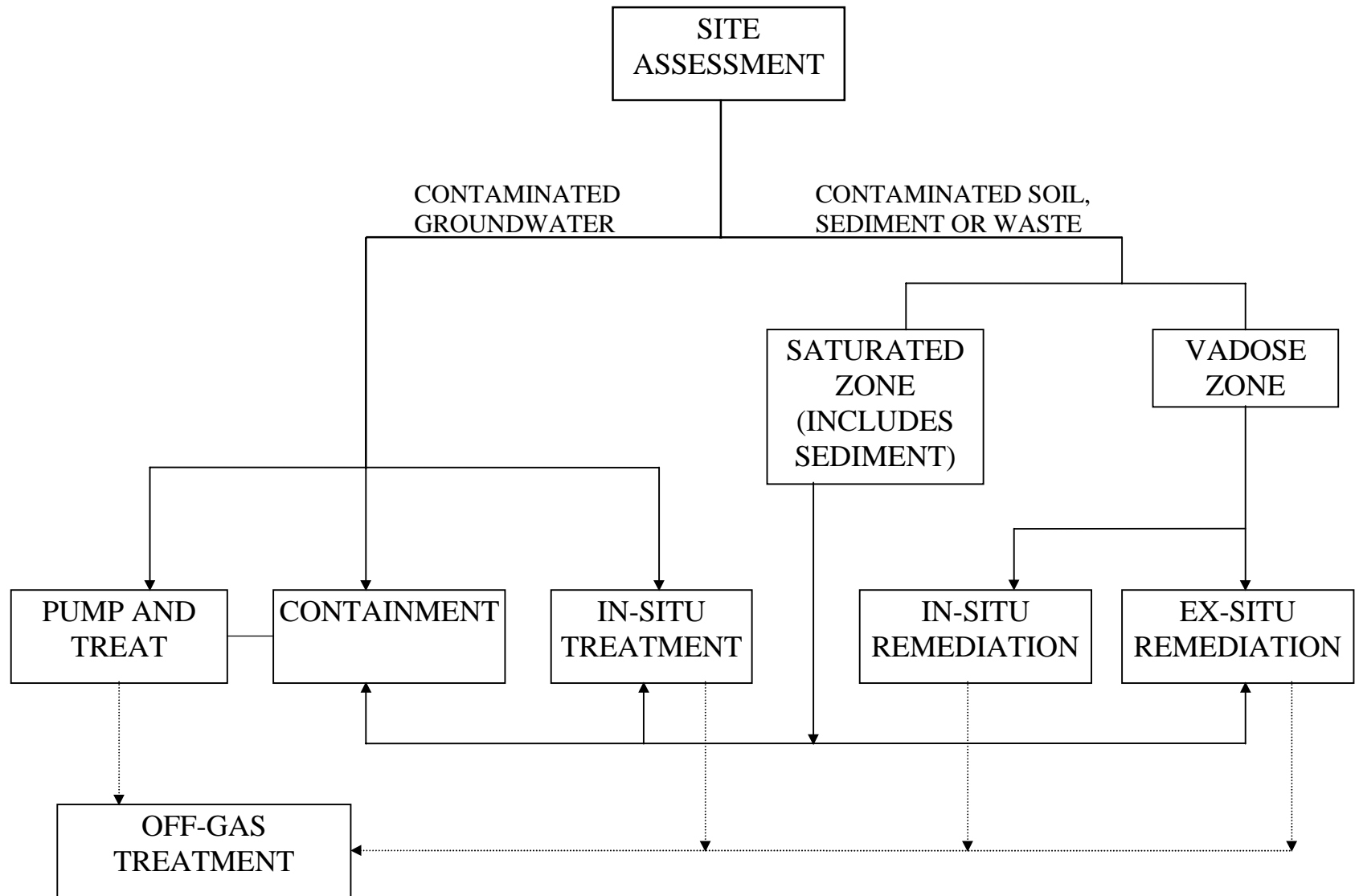


Figure 1.5 Flowchart of **general** remedial options for contaminated sites.

- **Step II: Screening of Alternatives**

- List all of the general remedial options including the “no action” alternative (see Figure 1.5)
- Screen out options which are not environmentally acceptable and those not technically feasible. The reasons for screening out options must be documented
- List all the sub-options of the remaining general options
- Screen out sub-options which are not acceptable for the same reasons as above

- **Step III: Selecting the Preferred Alternative**

There are a number of methods which can be used to select the preferred alternative from the list of sub-options developed in Phase II:

- Weighted scoring system
- Cost/benefit analysis
- Consensus of stakeholders
- Open or closed bidding (competitive bid)
- Treatability competition (choose technology which meets criteria at lowest cost)

In all cases the decision-making process should be documented in writing. Lastly, it should be noted that, for projects for which public consultation is required, the comments of the public need to be incorporated into the decision-making process. Meetings with the public, early in the decision-making process, are preferred because the public is then allowed to be involved in the process instead of being informed after decisions have been made.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 2: IN SITU TREATMENT OF SOIL AND GROUNDWATER

In situ remediation technologies are applied in place without excavating soils and sediments, or extracting groundwater. These technologies can be used to clean up soil in the unsaturated zone, or soil and groundwater in the saturated zone.

2.1 Overview

This chapter discusses advantages and disadvantages of *in situ* treatment, when compared with *ex situ* treatment. The discussion presents considerations for determining the feasibility of using *in situ* treatments.

A table identifies technologies used to treat contaminated soil, sediment and groundwater *in situ*. The accompanying section briefly describes these technologies, explains how they work, and identifies their advantages and limitations.

To consolidate information on the variety of technologies discussed, another section of the chapter compares treatment costs and factors which influence these costs.

The chapter also provides recommendations for using these technologies, as well as a summary.

2.1.1 Advantages of *in situ* Treatment

Relative to *ex situ* technologies, *in situ* technologies may be a more cost-effective and less intrusive means of remediating contaminated soils, sediments and groundwater. Excavating contaminated material, as well as operating and maintaining facilities for *ex situ* treatments often result in higher costs for treatment on the surface.

Unlike *ex situ* remediation, *in situ* technologies can be used at a site with little disruption to ongoing operations. *In situ* treatments require neither heavy equipment for excavation, nor large above-ground surface areas for facilities for treatment technology equipment.

Because *in situ* remediation occurs with contaminated materials in place, it minimizes exposing humans and the environment to contaminants. In contrast, transferring subsurface contaminated materials to the surface increases the risk of exposure for the same receptors.

For the reasons given above, as well as others such as inability to excavate contaminated material, or political or public opposition to *ex situ* approaches, *in situ* treatment may often be the preferred approach to remediation.

2.1.2 Disadvantages of *in situ* Treatment

Despite their advantages, *in situ* technologies have technical limitations and are somewhat ineffective at contaminated sites where conditions are unfavourable. *In situ* technologies generally require longer treatment times than *ex situ* treatment technologies.

Site conditions influence both how *in situ* technologies perform as well as how effective they are. Site-specific factors which make *in situ* treatments less effective include low soil permeability, subsurface heterogeneities, contaminant distribution, obstructions to treatment zones, and process control limitations.

Low permeability soil may make it more difficult to effectively deliver treatment fluids (e.g. surfactants, oxygen) into the subsurface. As well, subsurface heterogeneities may cause treatment fluids to preferentially flow through zones of higher permeability. As a result, lower permeability zones are poorly treated or not treated at all. Fracturing, an enhancement technology described later in this chapter, provides a way to overcome this limitation.

The nature of contaminant distribution, such as the presence/absence of LNAPL or DNAPL, may dictate the overall feasibility of *in situ* treatment, as well as the type and sequence of treatments that may be required. When LNAPLs are present, for example, they are usually pumped to the surface rather than treated *in situ*. However, *in situ* treatments may be feasible for contaminants dissolved in groundwater. In terms of the timing of treatments, LNAPLs are the first type of contamination to be removed. Residual and dissolved contamination are treated next.

Obstructions on the surface or in the subsurface may limit access to zones of contamination. In these cases, it may not be possible to apply *in situ* technologies effectively.

It is difficult to control *in situ* treatment processes because contaminated material cannot be accessed for treatment from all sides. As a result, the contaminated material may not be cleaned up uniformly. By comparison, *ex situ* treatments do not suffer from this limitation.

2.2 Types of In-situ Remediation Technologies

As shown in Figure 2.1, *in situ* technologies can be applied to the unsaturated (vadose) zone, the saturated zone or both. The following section will briefly describe each of the technologies listed in this figure.

Contamination in the sub-surface may exist as free product floating on the water table, residual contamination in the unsaturated and saturated zones, and components dissolved in groundwater. This section will present technologies for dealing with each of these ways in which contamination can occur. Although these technologies are discussed separately, they may in practice be used either alone, or as part of a treatment train made up of several of them. As an example, recovering free product from the subsurface may involve technologies

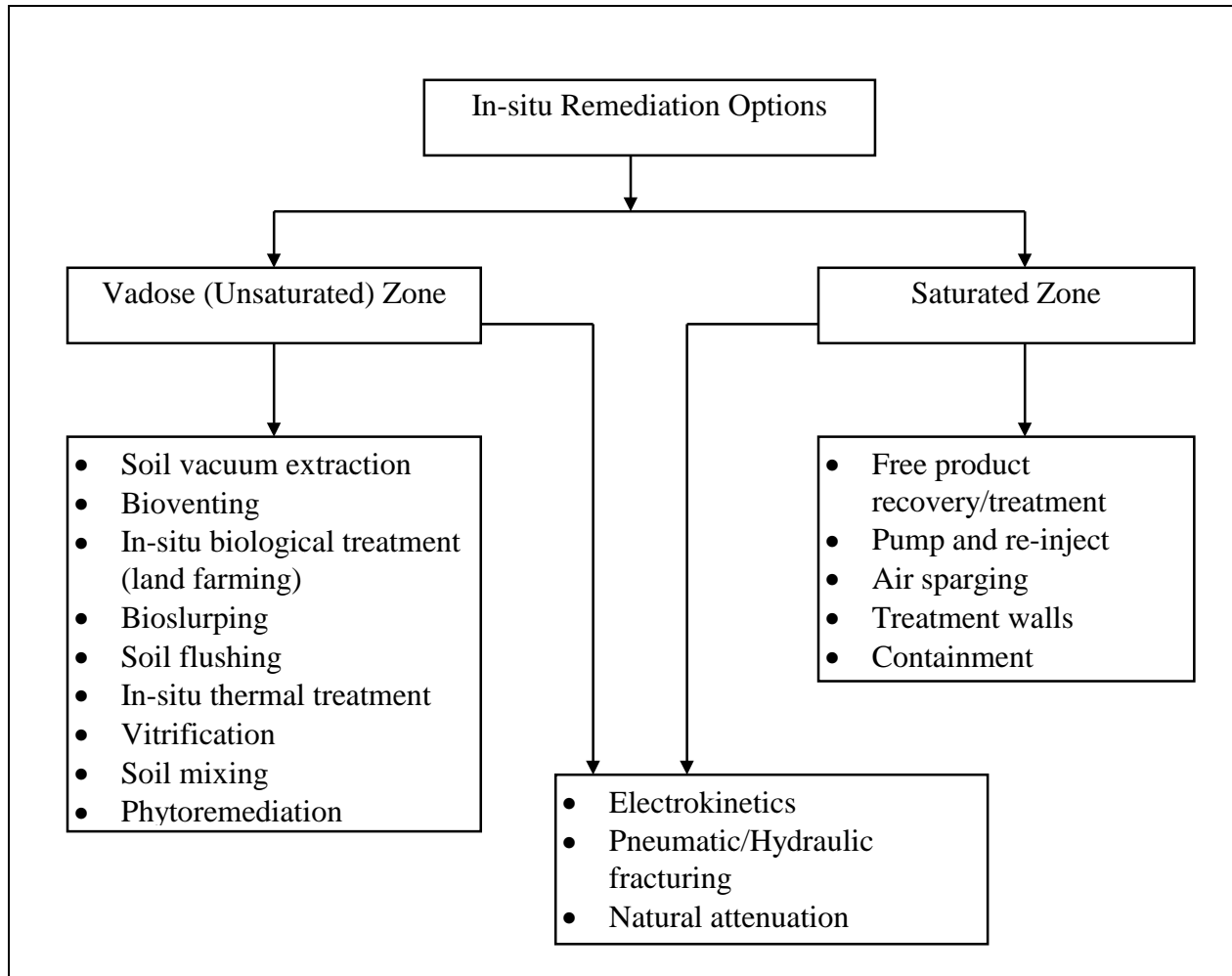


Figure 2.1 Technologies for treating contaminated soil and groundwater *in situ*.

for pumping free product and groundwater to the surface, separating the free product from the groundwater, treating the groundwater, and destroying or recycling the free products.

2.3 Soil Remediation in the Unsaturated Zone

Residual contamination in the unsaturated zone consists of contaminants adsorbed (ie. attached) to soil particles or trapped in voids between soil particles. Technologies for remediating this zone rely on subsurface conditions such as the presence of air (oxygen), the ability to move air through the soil, and the presence of microorganisms which can degrade the contaminants.

2.3.1 Soil Vacuum Extraction

Also known as soil vapour extraction (SVE), this technology reduces concentrations of volatile contaminants in the subsurface. It involves applying a vacuum to the subsurface to enhance the volatilization of contaminants and to transport them to the surface. Horizontal or vertical vent wells installed at strategic locations in and around a contaminated zone allow air to move from the surface and penetrate the subsurface.

In this application, a pump attached to a single extraction well creates a vacuum, pulls air through the subsurface, and removes contaminants in the extracted air. In this scenario, air enters the subsurface mainly from the surface rather than by vent wells. This approach works best when the subsurface is permeable enough to allow air to move freely through the system.

Capping may overcome short-circuiting near contaminated zones which are highly permeable. Capping the contaminated zone prevents air from moving directly from the surface to the extraction well and bypassing the contaminated zone (short-circuiting). Capping prevents air from following the easiest (direct) pathway to the extraction well and forces it to move through the contaminated zone. The technology has been proven, and has been used widely at contaminated sites in the U.S.

Use of SVE is limited to permeable unsaturated materials like sands, gravels and coarse silts, and to situations where the contaminants are volatile. If the contaminated soil lacks the air permeability required for SVE, fracturing may be used to increase air flow and increase vapour extraction. Fracturing is explained later in this chapter.

One disadvantage of SVE centres around having to treat air emissions (off-gases) containing contaminants extracted from the subsurface. Chapter 4 deals with technologies for treating off-gases. Another disadvantage is that a site containing contaminants with varying volatilities may require technologies other than, or in combination with, SVE to achieve remediation.

2.3.2 Bioremediation

By the process of biodegradation, microorganisms (e.g. bacteria and fungi) break down organic compounds and convert them to biomass, intermediate products, and byproducts such as carbon dioxide (CO₂), methane (CH₄), and inorganic salts.

Bioremediation technologies which rely on this process aim to influence the availability and concentration of contaminants and to control the rate of the reaction. Key environmental conditions which affect biodegradation include soil: pH (acidity or alkalinity), moisture content, temperature, and nutrient concentration.

Before implementing these technologies, the user should assess site conditions and conduct treatability studies to determine the feasibility of application. Assessing the site will reveal the concentration and types of contaminants, their distribution, the presence of microorganisms capable of destroying them, soil properties suitable for biological activity, etc. Treatability studies will determine the biodegradability of the contaminants, identify intermediates and byproducts, as well as disclose ways to enhance the process.

The following techniques apply to bioremediation:

Bioventing:

A slight variation of SVE, bioventing overcomes the limitation of off-gas treatment sometimes associated with SVE. This technology involves delivering oxygen to the subsurface to stimulate aerobic biodegradation of contaminants. By providing a constant supply of fresh air, microorganisms in the subsurface have oxygen to degrade contaminants *in situ*.

Injection and extraction wells (similar to vent and extraction wells for SVE) aerate the subsurface. Unlike SVE, which stresses a high air flow for contaminant volatilization, bioventing provides sufficient air flow to minimize off-gas production and encourage biodegradation in the subsurface. Bioventing may be enhanced by adding nutrients to the subsurface. This task, however, is sometimes difficult to do.

Bioslurping:

Bioslurping, an innovative technology illustrated in Figure 2.2, relies on a suction tube to remove free product floating on the water table and to ventilate the soil. This ventilation resembles bioventing in that it enhances volatilization and biodegradation of contaminants *in situ*. Contaminant vapours that reach the surface are discharged directly to the atmosphere, or treated.

Free product removal by this method is presented later under “Free Product Recovery”.

Land Treatment:

As mentioned earlier, bioremediation technologies aim to influence the availability and concentration of contaminants and to control the rate of the biodegradation reactions. Land treatment, normally applicable to surface soils, involves modifying soil properties in-place to enhance the microbial degradation of contaminants.

This approach may entail controlling key environmental conditions such as pH, soil moisture content, temperature, oxygen, and nutrient concentration, all of which affect biodegradation.

Tilling during land treatment helps to aerate the soil, as well as mix in amendments (such as wood chips, peat moss or special bulking agents), nutrients or microorganisms which can be added to the soil. In some cases, genetically engineered microorganisms (GEMS) or acclimated microorganisms (ie. those accustomed to their surroundings) may be added to the soil during treatment. Amendments or bulking materials added to the soil may enhance the soil's ability to hold water, increase its air permeability, or provide a source of carbon for the microorganisms. Of course, this approach is applicable only to biodegradable contaminants (e.g. polyaromatic hydrocarbons (PAHs) and pentachlorophenols (PCPs)).

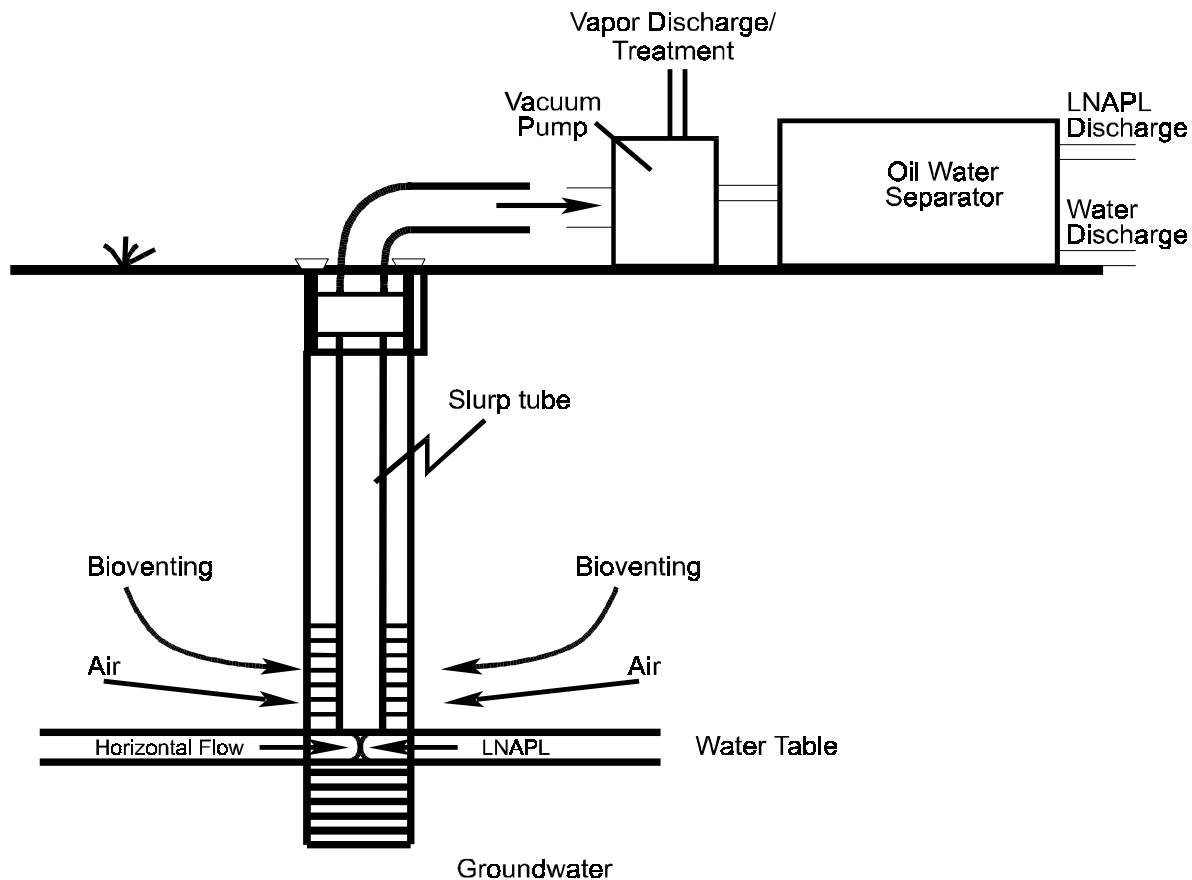


Figure 2.2 Schematic illustration of a bioslurping system. (from AFCEE, 1994).

2.3.3 Soil Flushing

Soil flushing involves delivering fluids into the subsurface to desorb or dissolve contaminants. Seen in Figure 2.3, the system relies on surface drains or infiltration galleries to deliver washing fluids to flood the subsurface. By means of shallow wells or subsurface drains, the elutriate (washing fluid and dissolved contaminant) is collected and pumped to the surface for treatment. The washing fluids may be recycled after the contaminants have been removed from them.

Because of the variety of fluids (water, sodium hydroxide, alcohols, etc.) which may be suitable for flushing, the technology can be tailored for both organic and inorganic compounds. The technology is easily applied to permeable soils, and the flushed-soil may not require further treatment. Costs are moderate, depending on the flushing solution used.

Conceptual Model

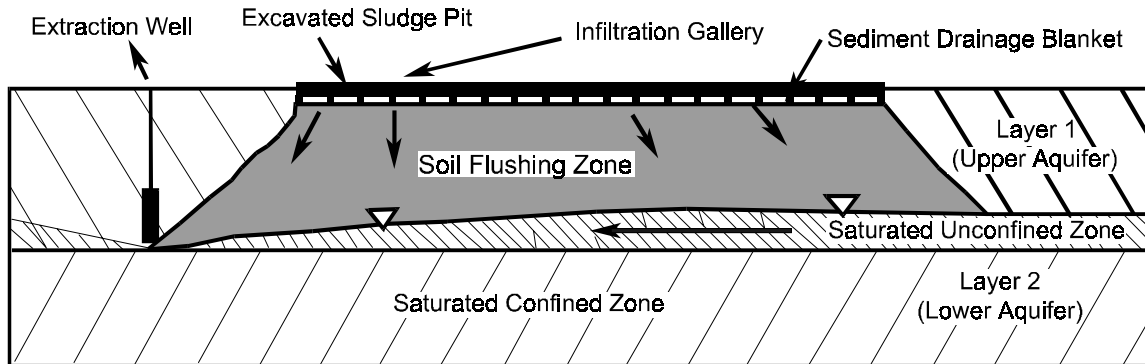


Figure 2.3 Illustration of a soil flushing gallery. (from Wastech, 1993).

One disadvantage of the technology is the demand to strictly manage and control the elutriate to prevent it from migrating away from the site and possibly contaminating groundwater or surface water elsewhere. Also, subsurface heterogeneities and low permeability conditions may severely impair the technology's performance. Despite its benefits, introducing potential toxic flushing agents to the subsurface alarms many potential users. They express concern as well about how the solutions may change the physical and chemical nature of the treated soil.

2.3.4 Thermal Treatment

Some thermal treatments aim to heat soil *in situ* to desorb and volatilize contaminants in the subsurface. In these applications, targeted contaminants consist of compounds such as aliphatic (straight chained hydrocarbon) and aromatic (ringed hydrocarbon) fractions of jet fuels and gasoline, and chlorinated compounds which typically volatilize between 80°C and 300°C. Instead of removing contaminants from soil, another type of *in situ* thermal treatment attempts to convert them into a chemically inert solid.

Volatilization:

These technologies include hot fluid injection (hot water, air or steam) radio frequency heating, and electrical resistance heating. After being extracted from the subsurface, volatilized contaminants are treated by any of the off-gas treatment technologies identified in Chapter 4.

A soil treated by steam stripping and radio frequency heating may not require further treatment. These two technologies are good for volatile and semi-volatile organics, in a permeable material such as sand.

One disadvantage of thermal heating is that it does not remove nonvolatile organics or metals from the subsurface. If these are present, other technologies will have to be considered. Further, heating a soil may adversely affect some of its properties.

Solidification:

By way of *in situ* vitrification, heat is used to convert contaminated soils into chemically inert glass and crystalline materials. When an electric current passes through electrodes inserted in a contaminated soil, the soil can be heated to as high as 3600^oC. At these temperatures, silicates in the soil melt to form a glass matrix, contaminants are pyrolyzed, and metals are volatilized. On completion of the process, the contaminated soil has been converted into a solid material resembling granite.

This innovative technology demonstrates many of the benefits of *in situ* treatments such as low exposure to contaminants and no need for excavation. An important advantage is the stable, glass-like material resulting from this approach.

Potential disadvantages of this technology are the need for skilled personnel to operate equipment, high energy consumption, and off-site migration of volatilized contaminants. Too much water in the contaminated materials can increase treatment time and result in higher costs.

2.3.5 Electrokinetics

Electrokinetics, used for several years to dewater soils, is now being used to treat contaminated sites.

As water flows through soil, negatively charged soil particles, such as clay, attract positive ions from the water. A layer of positive ions forms on the surface of these particles. When an electric field is applied to such a saturated soil, these positively-charged ions move toward the cathode. Concentrated solutions of these ions are extracted from near the cathode. Metallic ions in the soil are effectively treated with electrokinetics.

This technology is simple to apply, and contaminated soil solutions are easily extracted from where they collect. Remediation of the contaminated site is permanent.

While seen as an advantage, the ability to remove only metals proves to be a disadvantage of this technology. Thus, other technologies may be required if the site also contains organic contaminants. As well, excessive amounts of electrical power are required, making cost-effectiveness of this approach questionable.

An innovative aspect of this technology is its potential to remove metallic ions as well as hydrocarbons dissolved in groundwater. As ions move toward the cathode, they create a drag which causes water to flow toward the cathode and the collection area. This water may contain dissolved hydrocarbons. If successful, this technology will overcome the current limitation of removing just metals from the subsurface.

2.3.6 Phytoremediation

This innovative, low-cost technology uses plants possessing unique characteristics to accumulate, degrade or transform contaminants. These unique characteristics may be inherent in the genetic makeup of the species or, as is becoming more common, they may result from genetic engineering.

Plants used for this purpose degrade contaminants *in vivo* or within their rhizospheres. They can also accumulate contaminants in their roots and/or leaves.

This technology may be used at large sites where low level surficial contamination occurs. In this case, the sites can be remediated by cropping them with the specialized plant species. By harvesting the crop, contamination is removed from the soil. The harvested material may be treated to recover, destroy (e.g. by incineration), or concentrate the contaminants.

A prime benefit of this approach is that contaminated soil can be remediated *in situ* with minimal disturbance to the surroundings. At the same time, the treated soil has retained all of its natural physical, chemical and biological properties.

Disadvantages of the technology relate to the shallow depth of treatment and disposal of plants. This technology relies on plant activity so the depth of treatment is fairly shallow, being restricted to the root zone. Plants which accumulate rather than transform contaminants may have to be disposed of as hazardous waste. They cannot be used as feed because of their possible adverse effect on animals.

2.3.7 Natural Attenuation

Natural attenuation refers to a decrease in the amounts of contaminants at a site as a result of natural processes. These processes are classified as biotic (biological) or abiotic (non-biological). For this document, natural attenuation (passive bioremediation) is referred to as the inherent capacity of naturally-occurring micro-organisms to degrade contaminants.

In this process, micro-organisms consume the contaminants as a growth substrate (ie. food) in the presence of oxygen and other nutritional requirements. For natural attenuation to occur and be successful, a suitable environment must exist for the microbial population to flourish. The contaminants must be readily-available to the microorganisms (e.g., soluble in the soil pore water) and at a concentration that is non-toxic to the microorganisms.

Applying the technology involves first finding out if it is feasible, then monitoring it. To ensure that natural attenuation is feasible, one must first characterize the contaminated zone to determine if the environment is suitable. The zone may be supplemented with nutrients and other inputs to remove deficiencies. After applying the required inputs, the subsurface must be monitored to ensure that the contaminant is indeed being degraded.

As an approach for remediation, natural attenuation applies mainly to organic compounds. Candidate contaminants include BTEX, PAHs and selected chlorinated hydrocarbons. The technology is likely not useful for situations involving free product or residual NAPL.

2.3.8 Delivery/Recovery Systems

These systems deliver remediating materials to the subsurface or extract contaminants from this zone. The two systems discussed here combine the delivery of materials with the recovery of contaminants.

Soil Mixing:

This physical process consists of mixing soils *in situ* to promote delivery of reagents for immobilizing contaminants or to enhance recovery of these contaminants.

Techniques known as solidification/stabilization (discussed in Chapter 6), rely on mixing agents such as grout or lime with contaminated materials to immobilize them. Soil mixing is conducted from the surface. A large mixing paddle or auger breaks up the contaminated material and mixes it with the mixing agents at the same time. As a result of this mixing, contaminants are solidified or are converted into stable products.

The process of mixing causes some volatile contaminants to move into the vapour phase. This enhanced volatilization produces off-gases which are collected at the surface for treatment.

Pneumatic/Hydraulic Fracturing:

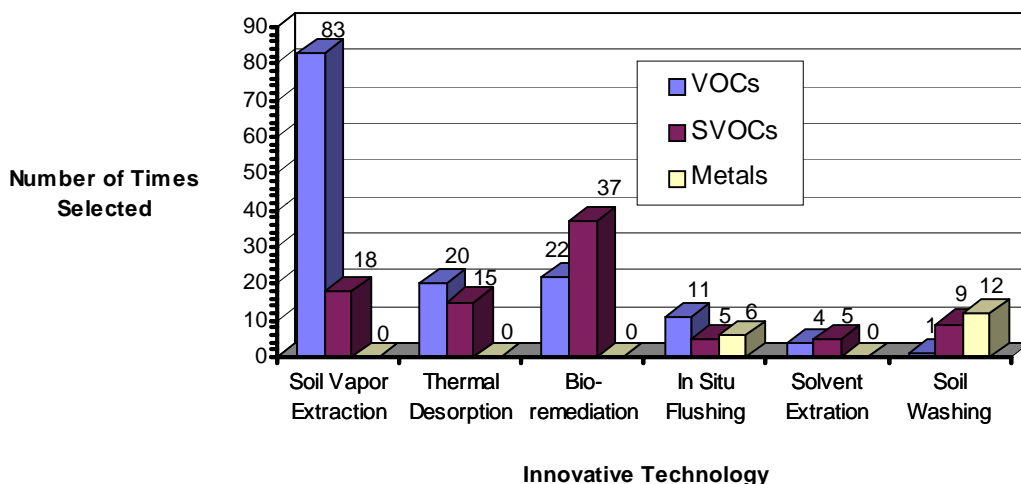
The petroleum industry uses this technology extensively to fracture reservoirs of low permeability and enhance recovery of hydrocarbons. Preliminary investigations for remediation applications suggest that this approach could be used on contaminated soil and rock. Fracturing is used to enhance pump-and-treat systems, or improve SVE in low permeability soils.

For remediation applications, pressurized air (for pneumatic fracturing) or fluid (for hydraulic fracturing) is injected into a low permeability material to generate fractures. Introducing a slurry of granular material (sand) and gel into the newly-formed fractures keeps them open as highly permeable channels for delivering remediating materials, or recovering contaminants by enhanced pump-and-treat or enhanced SVE.

2.3.9 Technologies Frequently Used to Remediate the Unsaturated Zone

Statistics on remediation technologies used at contaminated sites in the U.S. (Figure 2.4) reveal popular technologies for specific contaminants.

For VOCs, SVE was the favorite, followed by bioremediation and thermal desorption. Bioremediation surpassed both SVE and thermal desorption as the technology used for semivolatile organics. For metals, soil washing (an *ex situ* treatment described in Chapter 6) proved to be more popular than soil flushing.



Note: At some sites, treatment is for more than one contaminant and more than one treatment technology may be used. Treatment may be planned, ongoing, or completed. Adapted from: U.S. EPA, Technology Innovation Office, *Innovative Treatment technologies: Semi-Annual Status Report*, EPA/542/R-92/001, October 1992.

Figure 2.4 Statistics on the frequency of use of some innovative technologies in the US.

	Soil Vapor Extraction	Bioventing	Thermal Techniques	Surfactant Flushing	Soil Mixing	Hydraulic Fracturing	Pneumatic Fracturing
Applicability	Volatile fractions	Middle distillates	Gasoline, diesel and crude oil	Diesel and crude oil	Volatiles & semi-volatile.	Massive clay formations	Massive clay formations
Strengths	Proven technology	Low cost ^(f)	-Improved HC recovery	Residuals reduction	-Fast ^(f) -Enhanced mass trans.	Reduce diffusion path length	Reduce diffusion path length
Limitations	Low K layers in strat. soils	-Slow ^(f) -Low K layers	-Non-uniform heating -High cost ^(f)	-Emulsions -High cost ^(f) -Limited experience	-Large equipment -Boulders -High cost ^(f)	-Overconsolidated geology only -Surface heave	-Geology -Surface heave -Fractures close with time
Costs (\$/yd3) ^(a)	\$24 ^(b)	\$23 ^(b)	\$62 ^(c)	\$65 ^(d)	\$125	\$6 ^(e)	\$7 ^(e)
Time to Closure ^(a)	9 months	2 years	50 days	64 days	50 days	3 weeks (fracturing only)	3 weeks (fracturing only)
Availability	Widespread	Widespread	Sparse	Very limited	Sparse	Very limited	Very limited
Complementary Technologies	-Fracturing -Dewater	-Fracturing -Warming	-Fracturing -SVE	Fracturing	Heating	All fluid flush technologies	All fluid flush technologies

Notes:

- (a): Costs were calculated from information provided in the papers included in this report; closure refers to gasoline cleanup from 1000 to 2000 ppm in stratified site, with 100 ft x 100 ft x 15 ft source dimension.
- (b): Includes \$15k for design, \$20k for a pilot study and \$20k for pre and post-soil sampling.
- (c): Assumes steam stripping.
- (d): Assumes 80% recycling of the surfactant.
- (e): Costs are for fracturing only, not subsequent remediation.
- (f): Relative to other technologies described in the report.

Table 2.1 Technology comparison matrix for some innovative technologies. (Adapted from API, 1995)

2.3.10 Summary and Comparison of Technologies for the Unsaturated Zone

For most of the technologies presented in the last section, Table 2.1 summarizes and compares their applicability, strengths, limitations, costs, time to closure, availability and complementary technologies.

This table can be used to screen technologies before choosing one of them. For example, if the permeability of subsurface materials is low, fracturing may be considered as a complementary technology. Similarly, volatile contaminants in a highly permeable subsurface may be treated by SVE. When cost and treatment times are important considerations, it is best to first choose several treatment options, then select the one which matches the proposed cleanup costs and timeframe for remediation.

2.3.11 Treatment Costs and Factors Affecting Cost

Figure 2.5 summarizes and compares costs for several *in situ* options for treating contaminants in the unsaturated zone. Technologies listed in this figure are *in situ* solidification/stabilization, SVE (off-gas not treated), SVE (off-gas treated), bioremediation, bioventing, *in situ* vitrification, radio frequency heating, soil flushing and steam/hot air injection and extraction. Radio frequency heating, a thermal treatment, is mentioned briefly under “Treatments for Volatilization”.

The cheapest technologies are among those used most often to clean up contaminated sites. These are SVE (with or without off-gas treatment), bioremediation and bioventing. The other technologies, except for *in situ* vitrification, cost about the same but may not be used as often because they deal with unique contamination situations. In contrast to these technologies, high energy requirements make *in situ* vitrification extremely expensive.

Low permeability of the subsurface increases remediation costs. For technologies which depend on the flow of fluids (air or water), poor fluid flow in low permeability soils will result in longer cleanup times and higher costs. For six such technologies listed in Figure 2.5, low air conductivity or low hydraulic conductivity are factors that increase costs. As expected, biological treatments become more expensive if the ambient temperature is low. Added costs are incurred to increase the ambient temperature and enhance biodegradation.

2.4 Soil and Groundwater Remediation in the Saturated Zone

In the previous section we have discussed the remediation of soil in the unsaturated or vadose zone. Now we will discuss the remediation of soil and groundwater in the saturated zone or the zone below the water table. In this zone it is difficult to distinguish between soil and groundwater remediation because the two media are in intimate contact with one another and because the chemical interactions between the soil and the groundwater are continuous and dynamic. The only method to treat the soil in the saturated zone separately from the groundwater is to excavate the soil and treat it ex-situ (discussed in Chapter 6) and then treat the groundwater which collects in the excavation.

Another topic which is included in this section is the remediation of “free product”. Free product is often a hydrocarbon such as gasoline, jet fuel, heavy oil or coal tar but sometimes is

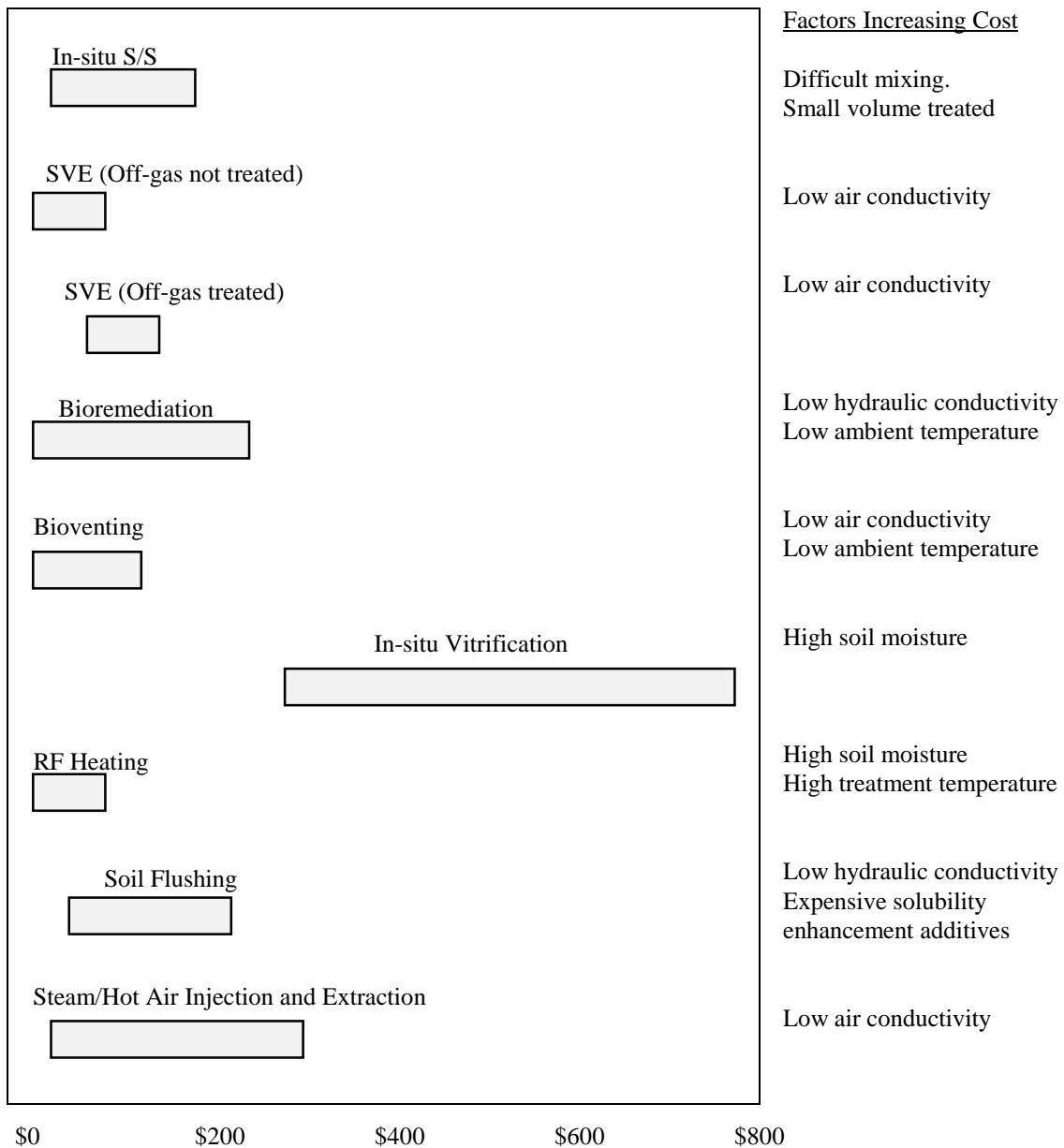


Figure 2.5 Cost ranges (in US funds) for some in-situ treatment technologies. (from Smith and Houthoofd, 1995)

another organic liquid such as PCBs or perchlorethylene. As discussed in Chapter 1, free product may be a lighter than water (a LNAPL) or denser than water (a DNAPL) and therefore may be found either floating on the water table or pooled below the water table, usually on an impermeable layer of clay or bedrock (an aquitard).

2.4.1 Pumping of Free Product

Special pumps recover free product (LNAPL) floating on the water table. A pneumatic skimming pump transfers LNAPL with a small amount of groundwater to a separator on the

surface. Note that this application does not lower the water table. By way of the separator, LNAPL and the groundwater are separated. The LNAPL is skimmed off and subsequently destroyed or recycled while the groundwater may have to be treated. Chapter 3 provides more information on separators.

A two-pump free product recovery system consists of two pumps which pump two separate liquids (LNAPL and groundwater) to the surface. Unlike the skimming pump application described above, this one may form a cone of depression which may result in smearing. Controlled pumping minimizes water table fluctuation and the problem of smearing. On the surface, the LNAPL is destroyed or recycled, and the groundwater may be treated to remove dissolved contaminants.

2.4.2 Bioslurping

An innovative technology called bioslurping combines free product recovery and soil venting. Section 2.3.2 of this chapter examined the bioventing component of the technology. The technology, as illustrated in Figure 2.2 consists of a slurp tube to extract LNAPL and water, and a pump which creates the vacuum for the “slurping” and bioventing. On the surface, an oil/water separator separates the liquid streams. The oil may be destroyed or recycled, while the water may require treatment before being discharged. Chapter 3 discusses some of the options for treating extracted water on the surface.

2.4.3 Groundwater Pump and Treat Systems

Pump and treat is the technology most commonly used for contaminated groundwater. Seen in the past as a technology for cleaning up contaminated sites, pump-and-treat is now used to contain contaminated material rather than to remediate a site.

Pump and treat systems did not live up to the original promise of cleaning up contaminated sites. When users first applied the technology in the field, they believed they could achieve clean-up criteria by removing sufficient pore volumes of groundwater from the zone of contamination. In calculating pumping (clean-up) timeframes, technology users originally assumed the subsurface was homogeneous and isotropic (equal in all directions).

These subsurface conditions, rarely found at contaminated sites, suggested that pump and treat could clean up a contaminated site in a relatively short time. Field data, however, did not support this prediction. Case study after case study confirmed that the assumption of homogeneous and isotropic conditions in the subsurface was flawed, and that pump and treat systems will usually require longer periods of time to achieve clean-up.

Although several factors may influence clean-up times, subsurface heterogeneities likely have the greatest impact. Heterogeneity in aquifers, illustrated in Figure 2.6, causes groundwater to follow preferential flow paths along zones of high permeability. As seen in the velocity profiles in Figure 2.6, groundwater flows fast in sand and gravel, slowly in sandy clay or clay, and is likely retarded by tight clay. Because extraction favours flow in the higher permeability zones, little groundwater may be extracted from the lower permeability zones. As a result of this poor access to lower permeability zones and the preferred flow through the higher permeability zones, large volumes of groundwater may have to be extracted to achieve clean-up goals.

Contaminant distribution, like groundwater flow, differs in high and low permeability materials. However, the low permeability material may contain higher concentrations of contaminants. These materials have a smaller average particle size (hence greater surface area) and greater content of natural organic matter. Because of these two properties, low permeability materials have a high adsorption capacity for contaminants, resulting in a higher content of contaminants.

Varying groundwater velocity and contaminant distribution in the different types of subsurface materials have important implications for applying pump and treat. Using the situation shown in Figure 2.6 as an example, if water is being pumped from all layers at the same time, most of the water would come from the sand and gravel. As mentioned before, these layers may contain less contamination than the clay and silt layers. As a result of these variations, water pumped to the surface may contain small amounts of contaminants extracted mainly from the sand and gravel layers, while the bulk of contaminants remain in the subsurface in the low permeability clay and silt layers.

By recognizing the limitations of pump and treat systems, users of these systems now employ them for containment of contaminants rather than timely clean-up. For this manual, information on pump and treat systems will focus on containment (Chapter 5) and treatment of extracted groundwater (Chapter 3).

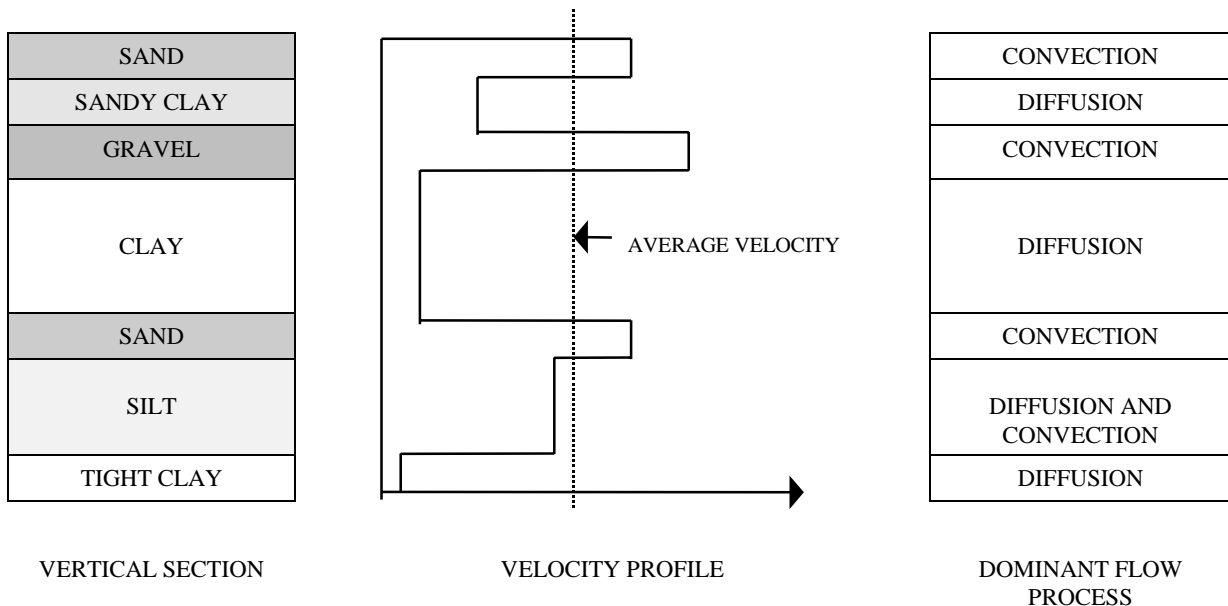


Figure 2.6 Illustration of differences in transmissivity and dominant flow processes in different media (from Keely, 1989)

2.4.4 *In Situ* Bioremediation:

In situ bioremediation has been used, in practice, primarily to clean up sites containing petroleum hydrocarbons. Despite its successes, oxygen is usually the main limiting factor. To overcome this limitation, several approaches are used to deliver oxygen, nutrients and other supplements to the subsurface.

Pump-and-Reinject:

Pump-and-reinject focuses on stimulating biodegradation *in situ*. It involves extracting groundwater, adding amendments to it, then reinjecting it into the subsurface.

The schematic in Figure 2.7 simplifies how the technology is used. In this demonstration, groundwater water is taken out of the ground through an extraction well, reagents are added, then the water is returned to the ground through a recharge well.

Biodegradation and soil flushing occur in the subsurface. Amendments added to reinjected water stimulate microorganisms and promote biodegradation. Also, as reinjected water moves toward the extraction well, it flushes contaminants from the soil.

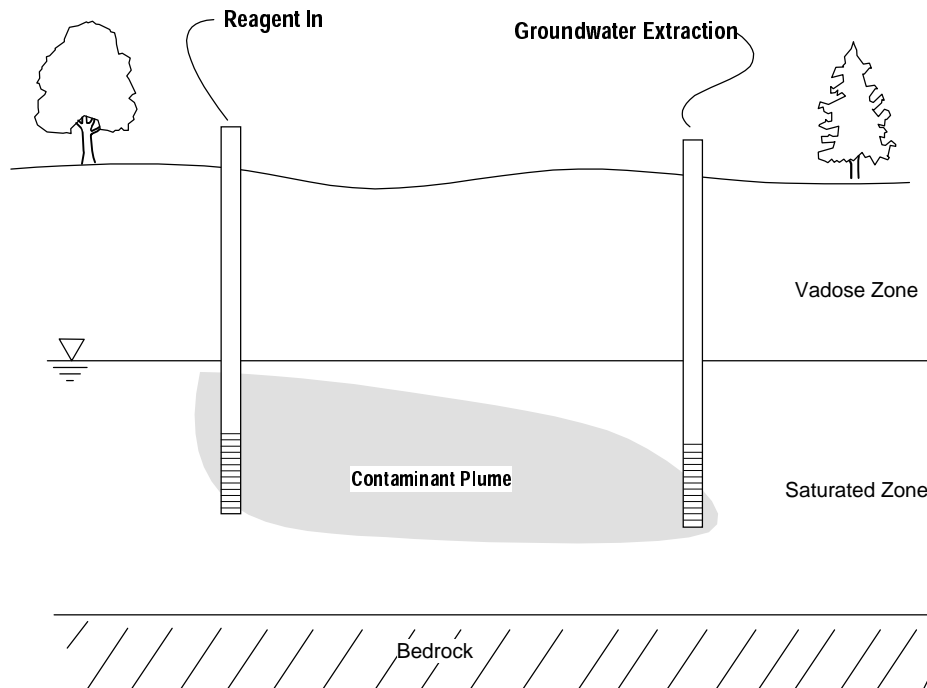


Figure 2.7 Illustration of a groundwater pump and re-inject system.

Figure 2.8 provides more details of the surface component of a pump-and-reinject system designed to clean up both contaminated groundwater and soil. In this above-ground treatment train, a physical/chemical system treats extracted water to remove metals. After this step, microorganisms in the bioreactor (bioreactor) degrade organic contaminants.

Some of the effluent from the bioreactor is then applied to the soil and allowed to percolate. This effluent contains active biomass which degrades contaminants in the soil. A clarifier separates solids and liquids in the rest of the effluent which remains on the surface.

Air Sparging:

Air sparging offers great potential to clean up contaminated sites. The technology offers two remediation approaches working alone or together. They are bioremediation and volatilization.

The process involves introducing air beneath the water table. Air under pressure is injected directly into the aquifer to provide oxygen for biodegradation and/or to strip contaminants from groundwater. As volatilized contaminants move toward the surface, they may be captured by a vacuum extraction well and pumped to the surface for treatment.

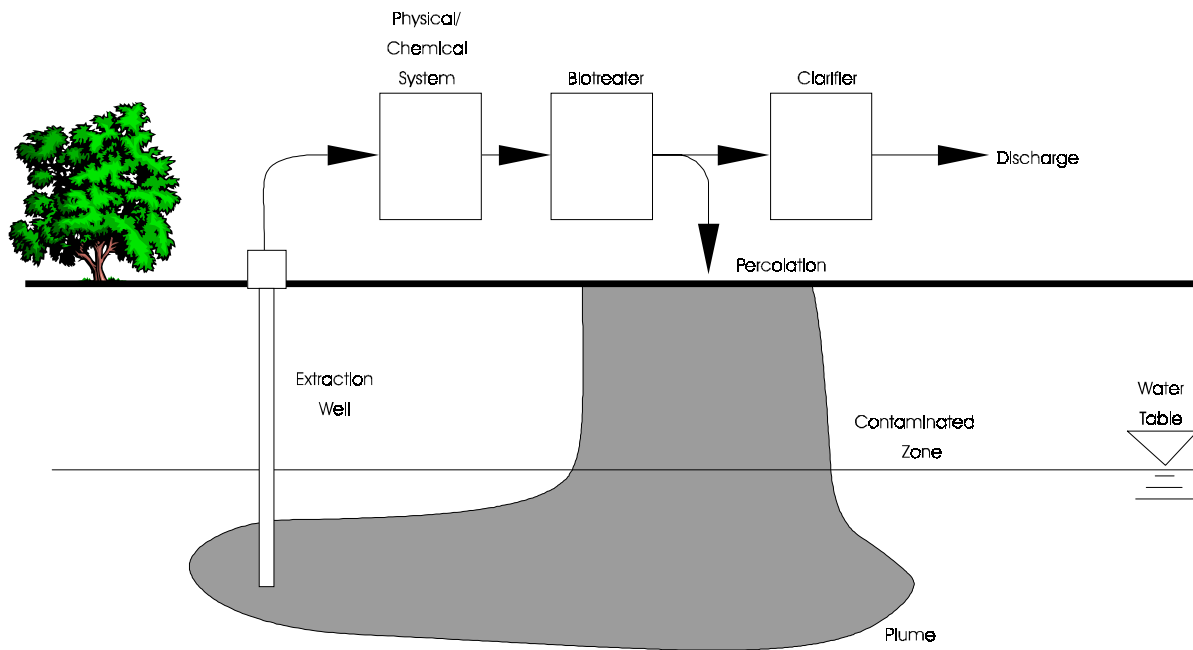


Figure 2.8 Illustration of a pump, treat and re-inject system.

Hinchee (1994) reported that the air appears to migrate as a separate phase rather than as bubbles, and to follow channels in the subsurface. Through diffusion in these channels, oxygen is transferred from the air to the water, and contaminants move from the water to the air. As a result of this channeling, some parts of the aquifer are exposed to injected air, and other parts are not. Thus, biodegradation will likely occur only near flow paths where oxygen is available.

2.4.5 Treatment Walls

Unlike “active” remediation systems which depend on equipment such as pumps and surface treatment, treatment walls are considered to be a form of “passive” treatment because they require minimal monitoring and maintenance. This approach, as seen in Figure 2.9, involves installing a permeable wall to intercept contaminated groundwater. The wall consists of an excavated ditch filled with a permeable medium such as sand or gravel to improve groundwater flow, as well as materials to precipitate, sorb or degrade the contaminants. For example, iron filings in treatment walls are being tested as a way to degrade chlorinated compounds dissolved in groundwater.

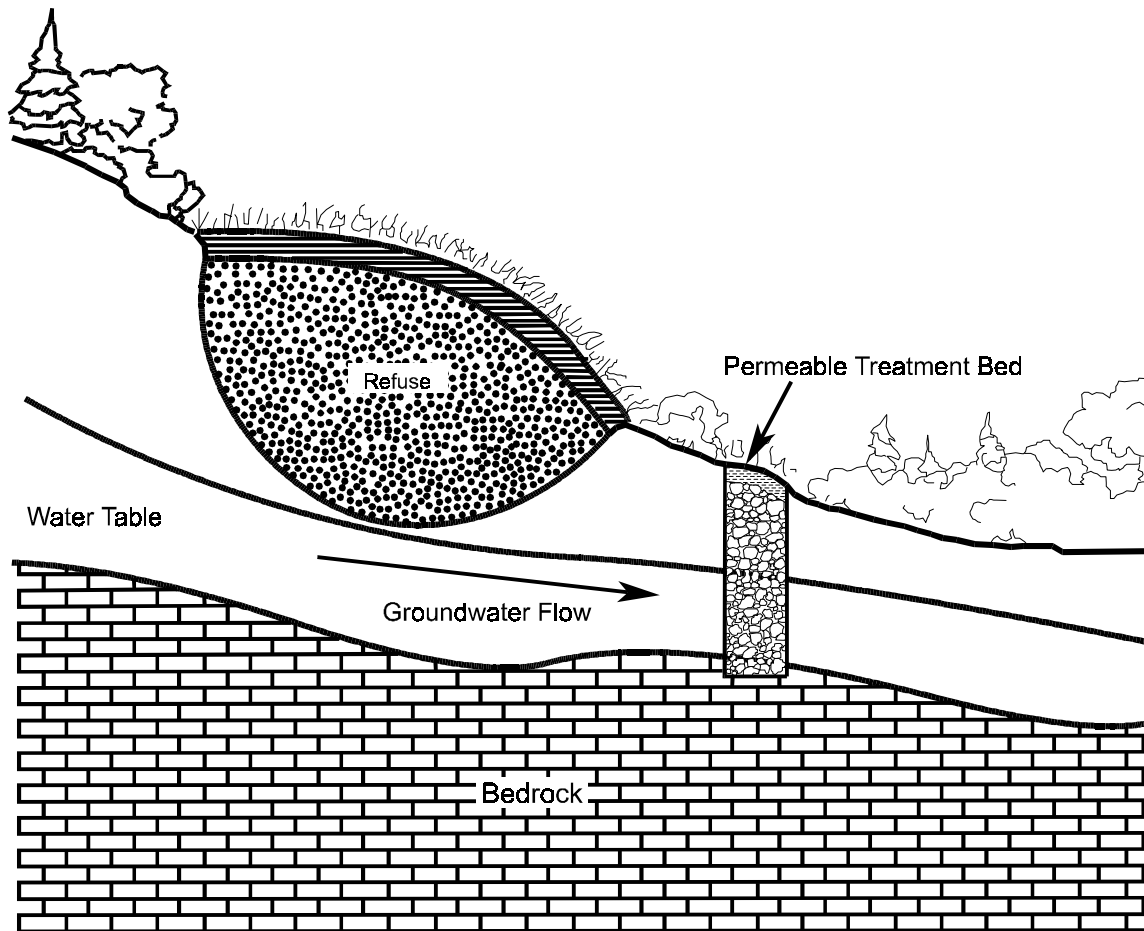


Figure 2.9 Illustration of treatment wall. (from Wagner et al, 1986)

One advantage of these walls is their low maintenance. Frequent monitoring is not required and the walls may remain in place for long periods of time before having to be replaced. In contrast, the approach has a disadvantage of having high installation costs especially when the walls have to be installed to capture water in deep aquifers.

Treatment walls are relatively new as a remediation technology, so their long-term stability has not been established. Nevertheless, they promise to be an economical approach in situations where a long treatment time is envisaged.

2.4.6 Natural Attenuation

As mentioned before, natural attenuation refers to a decrease in the amounts of contaminants at a site as a result of natural processes. These processes are classified as biotic (biological) or abiotic (non-biological). For this document, natural attenuation (passive bioremediation) will refer to the inherent capacity of naturally-occurring micro-organisms to degrade contaminants.

The earlier discussion focused on passive bioremediation in the unsaturated zone, but this process can also occur in aquifers. As mentioned for the unsaturated zone, unique conditions in the saturated zone will influence attenuation rates. These conditions, as well as the anticipated attenuation rates can be factored into equations for risk assessment to determine if remedial actions will be needed at a contaminated site.

The previous text on natural attenuation (section 2.3.7) provides more information on the process.

2.4.7 Technologies Most Frequently Used for Remediating the Saturated Zone

Pump-and-treat continues to be the most popular approach for managing contaminated groundwater. As mentioned before, this approach is now seen as a way to hydraulically contain contaminated groundwater and not to remediate a contaminated site.

Vertical or horizontal wells are used for pumping groundwater to the surface. In situations where the subsurface consists of low permeability materials, pneumatic or hydraulic fracturing is used to enhance recovery of groundwater.

Earlier parts of this chapter presented several technologies for treating extracted groundwater. Of these, air stripping and adsorption with carbon are most commonly used.

2.5 Summary

In situ remediation technologies offer several advantages over *ex situ* approaches. For example, *in situ* remediation tends to be relatively cheaper, does not depend on large spaces for surface equipment, and does not disrupt on-going operations at a site. Despite these advantages, uncertainties about the effectiveness of *in situ* treatments can sometimes favour *ex situ* approaches.

Several *in situ* technologies depend on effectively moving fluids such as air and water through the soil. Examples of these technologies are SVE, bioremediation, bioventing, soil flushing, pump-and-reinject, and air sparging. If the subsurface is not permeable enough for these approaches to be used, fracturing may be used to enhance the soil's permeability.

For other *in situ* technologies, permeability is not as crucial a requirement. Approaches such as soil mixing and land treatment achieve their goals by mixing the soil. Others like thermal treatment, vitrification and electrokinetics use heat and / or electricity to remove contaminants from the subsurface or to fix them in place.

Other *in situ* approaches are "less active". Examples are natural attenuation and treatment walls. They may require very long treatment times, and may consist of long-term monitoring to determine the effectiveness of the approach.

Statistics on technologies used at contaminated sites reveal which are the most popular. In the unsaturated zone, SVE and bioventing were most commonly used. In the saturated zone, pump-and-treat continues to be the preferred option.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 3:TREATMENT OF EXTRACTED GROUNDWATER

Ex situ treatment of groundwater by “pump and treat” consists of extracting contaminated groundwater, treating the extracted water, and discharging or reinjecting treated water.

Pumping groundwater to the surface is a strategy which is intended to contain contamination in the subsurface by hydraulically preventing groundwater from flowing out of the contaminated zone. Although pumping and treating groundwater may result in partial remediation of soil and groundwater in the saturated zone, this approach should not be seen as a way to completely remove contamination from the saturated zone . In some cases the pump and treat option is the only one available or is less expensive than other options even if groundwater has to be pumped for many years.

3.1 Overview

This chapter focuses on approaches for remediating extracted groundwater through *ex situ* treatment. Technologies for treating groundwater *in situ* were discussed in Chapter 2. In this chapter, *in-situ* and *ex-situ* treatment techniques will be compared, the types of sites favouring *ex-situ* treatment and the types of contaminants normally found in pumped groundwater will be discussed and then *ex-situ* groundwater treatment technologies will be presented.

3.1.1 Comparison of In-situ and Ex-situ Technologies for Groundwater Remediation

While *ex situ* methods require extracting groundwater to the surface, *in situ* treatments do not always demand this. *In situ* biological treatment, for example, may consist of extracting groundwater, adding nutrients to the extracted water, then reinjecting it. On the other hand, nutrients could be added directly to the subsurface thereby avoiding the extraction step.

These two categories of technologies are best for treating different fractions of subsurface contamination. As mentioned in Chapter 2, *in situ* technologies treat sorbed (attached to particles) and residual contaminants. By comparison, *ex situ* technologies treat dissolved contaminants and free product in extracted groundwater.

In general, *ex situ* technologies require more above-ground space than *in situ* technologies. Applying *in situ* technologies may require extraction and injection wells, pumps and other small equipment. *Ex situ* technologies, in contrast, require pumps as well as larger equipment to treat extracted groundwater. These different space requirements may influence which type of technology is used at a site.

In comparison to treating contamination *in situ*, extracting contaminated materials for treatment on the surface may pose a greater risk of exposing humans and the environment to the contaminants. In the case of extracted groundwater, this increased risk could result from

possible exposure to contaminated off-gases generated by some *ex situ* treatment technologies, and by spills.

If *in situ* and *ex situ* treatment technologies were applied to identical volumes of groundwater containing the same contaminants, treatment times for the *ex situ* technologies would be relatively shorter. It is usually easier to monitor and optimize the performance of *ex situ* technologies. This optimization will usually decrease treatment times.

In situ treatments are generally cheaper than those using *ex situ* approaches. *Ex situ* technologies usually require above-ground equipment, buildings to house the equipment, frequent monitoring to ensure that the treatment system is operating efficiently, and maintenance. All of these items make *ex situ* treatments more expensive.

An important advantage of *ex situ* remediation technologies centres around the ease of monitoring their effectiveness. For example, sampling is easy, and the source of samples is readily identified. In the case of *in situ* treatments, sampling soil and groundwater is more difficult, making monitoring somewhat less effective.

Table 3.1 compares some aspects of *in situ* and *ex situ* technologies for treating contaminated groundwater.

3.1.2 Situations Favouring *Ex Situ* Treatment of Contaminated Groundwater

Subsurface conditions and the nature of contamination both influence the ability to pump contaminated groundwater to the surface and treat it *ex situ*.

	<i>In Situ</i>	<i>Ex Situ</i>
-Groundwater extraction:	May be required	Required
-Occurrence of contaminant best treated	Sorbed/residual	Dissolved
-Above-ground surface area required:	Minimal	Extensive
-Exposure to humans:	Minimized	Increased
-Treatment times required:	Longer	Shorter
-Cost:	Low-medium	Medium-high
-Monitoring effectiveness of clean-up:	Difficult	Easy

Table 3.1 Comparison of *in situ* and *ex situ* technologies.

Ex situ treatment of contaminated groundwater involves first pumping the groundwater out of an aquifer. Aquifer properties which favour pumping are:

- relatively simple stratigraphy;
- fairly homogeneous unconsolidated aquifer materials; and
- significant hydraulic conductivity.

Contaminants existing mainly as dissolved constituents in groundwater are easily pumped to the surface for treatment. Contaminants adsorbed to aquifer materials or trapped in voids are not readily removed by pumping.

3.1.3 Constituents to be Removed from Extracted Groundwater

In addition to contaminants, extracted groundwater may contain other constituents which have to be considered as part of the overall treatment. These nuisance constituents are usually not hazardous however, if they are not removed during a pre-treatment step, they can diminish the performance of technologies that target organic contaminants.

Constituents normally removed from extracted groundwater are:

- nuisance inorganics (e.g., iron and manganese);
- suspended solids;
- free product (e.g. gasoline);
- dissolved organic contaminants (volatile and semi-volatile); and
- dissolved inorganic contaminants.

3.2 Types of Ex-situ Groundwater Remediation Technologies

The flowchart in Figure 3.1 shows a sequence of steps for treating extracted groundwater which includes all of the general types of treatment. Obviously, most treatment systems will not utilize all of these processes but may use as many as three of them in series.

This groundwater may be pre-treated, or sent directly to an air stripper or other water treatment systems. Pre-treatment removes nuisance inorganics or suspended solids. Pre-treatment having been completed, the water may be routed to an air stripper or other water treatment system.

Water that has passed through an air stripper generates two streams: off-gases and treated water. Depending on the jurisdiction, the off-gases containing contaminants transferred from the groundwater may be vented directly or require further treatment. Chapter 4 discusses off-gas treatment technologies.

The following section of this chapter describes some of the technologies for treating raw extracted groundwater, and water that has been pre-treated and/or air stripped.

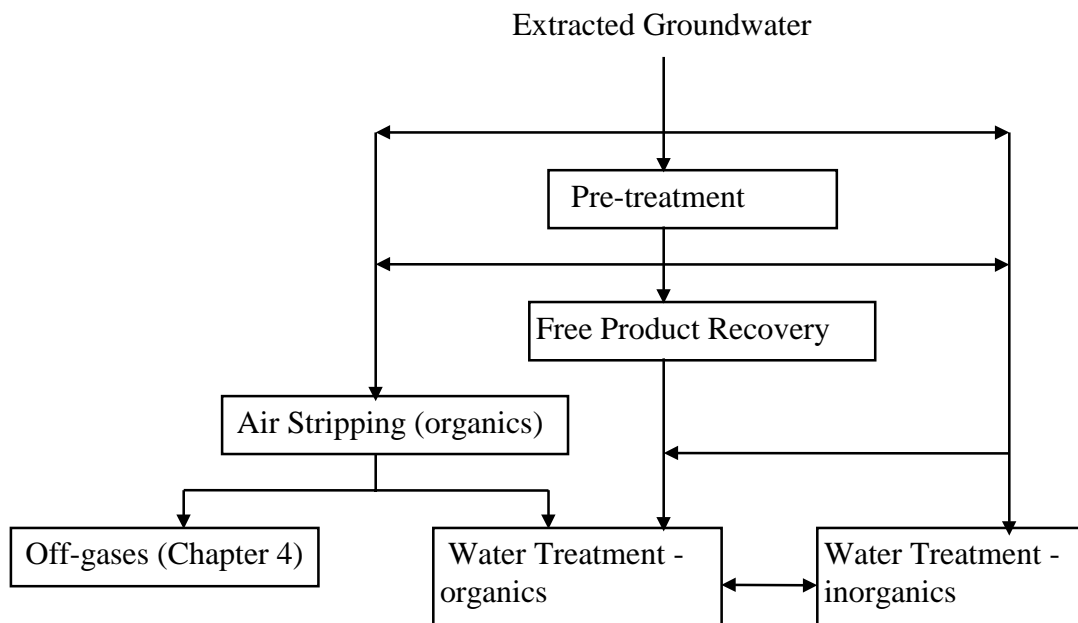


Figure 3.1 Sequence of possible steps for treating extracted groundwater.

Table 3.2 identifies commercial and developing technologies for treating organic and inorganic contaminants in extracted groundwater. Commercial (conventional) technologies are those which are available commercially and are commonly used to remediate contaminated sites. Innovative technologies are those which have been tested, selected or used for treating hazardous waste or contaminated materials, but lack well-documented cost and performance data under a variety of operating conditions.

3.3 Free Product Recovery

Separators are used to recover free product from extracted groundwater and are limited to separating immiscible phases from water. This process relies on the density difference between water and recoverable free product to separate the two fluids. They are used extensively to separate refined petroleum products, such as oil and gasoline, from water.

A separator is usually comprised of a tank with baffles to prevent short-circuiting. Extracted groundwater enters at the top of one end of the separator and separated oil is skimmed off the top, while treated water leaves at the other end. The separated oil may be recycled, or destroyed in incinerators as described in later sections.

After passing through the separator, extracted groundwater which contained petroleum products may retain between 10-100 mg/l Total Petroleum Hydrocarbons (TPH). Treated water may be discharged to sewers, or passed through secondary treatment systems such as activated carbon units. These units will be described later in this chapter.

1. Organic Contaminants	
Separators	Commercial
Air strippers	Commercial
Steam Strippers	Some commercial
Activated carbon filters	Commercial
Membranes	Commercial
Oxidation systems	Commercial being developed
Activated sludge bioreactor	Commercial
Fixed-film bioreactor	Commercial
Biophysical	Commercial, PACT process
2. Inorganic Contaminants	
Alkaline precipitation	Commercial
Coagulation	Commercial
Ion exchange	Commercial
Adsorption	Commercial
Filtration	Commercial
Reduction	Commercial
Membranes	Commercial; membranes being developed
Oxidation	Commercial

Table 3.2 *Ex situ* treatment technologies and their stage of development.

Treatment rates and cost depend on factors such as the size of the separator, influent concentration, and the removal efficiency. For units treating 5-100 gallons-per-minute (gpm), capital costs can range from 2,000 C\$ to more than 50,000 C\$. A large portion of operating costs, estimated at \$0.25 to \$3.00 / 1000 gal., are due to the removal and disposal of pure phase product.

Benefits:

Separators are readily available, proven, relatively inexpensive to operate, and require little maintenance.

Disadvantages:

This technology does not remove dissolved contaminants. Biological fouling may occur, and volatile contaminants may be lost to the atmosphere. Separated product has to be removed regularly.

Treatment of Recovered Free Product:

Recovered free product may be recycled or destroyed. A liquid injection incineration system can be used to destroy the LNAPL skimmed off the extracted groundwater. Destruction of the free product may result in off-gases which may have to be monitored to ensure that harmful by-products are not released to the atmosphere.

3.4 Groundwater Pre-treatment

In some cases, nuisance inorganics may be present in extracted groundwater and may require removal before the water can be subsequently treated to eliminate other contaminants. If not removed, these nuisance inorganics can diminish the efficacy of the treatment technology. The pre-treatment step involves chemical or physical methods that usually target dissolved iron and manganese, hardness, and suspended solids.

To achieve the water quality required by a treatment technology, a pre-treatment system may consist of one or more of techniques listed below:

- aeration: air is used to oxidize dissolved iron and manganese to produce inorganic precipitates.
- chemical oxidation: oxidizing agents such as hydrogen peroxide (H_2O_2), chlorine dioxide (ClO_2), and potassium permanganate ($KMnO_4$) convert dissolved iron and manganese to inorganic precipitates.
- pH adjustment: acids and alkalis adjust the pH to achieve water quality required by the treatment technologies.
- filtration: filters remove suspended solids already in extracted groundwater and inorganic precipitates formed during aeration and/or chemical addition.
- water softening: chemicals remove hardness from extracted water.

3.5 Groundwater Treatment for Dissolved Organic Contaminants

Organic compounds dissolved in groundwater are removed by techniques such as air stripping, oxidation, carbon adsorption, biodegradation, and membrane separation.

3.5.1 Air Stripping

By increasing the surface area of contaminated water exposed to air, volatile organic compounds dissolved in the water are transferred from the aqueous phase to the vapour phase. Several methods achieve this enhanced aeration. They include packed towers, diffused aeration, tray aeration, and spray irrigation. Most systems consist of a contact chamber (or tower), air blowers, pumps, piping and distribution systems.

In packed towers (air strippers), which are the most popular systems, contaminated groundwater and air flow counter-current to each other. A blower at the bottom of the tower forces air towards the top. Contaminated groundwater enters at the top of the tower and encounters the packing material while flowing to the bottom of the tower. Treated water leaving the tower may be discharged to surface drains or sewers, or treated further with carbon to achieve drinking water levels. Air emissions (off-gases) containing organic compounds stripped from the groundwater may have to be treated. Off-gas treatment is discussed in Chapter 4.

Air stripping systems target halogenated and non-halogenated volatile organic compounds. Units treat between 10-100 gpm. Capital costs range from 10,000 C\$ to 50,000 C\$, while operating costs fall between 0.05 C\$ to 3.00 C\$ per 1000 gal.

Benefits:

Air strippers are proven and are available commercially. USEPA (1993a) reports that more than 1,000 units are in operation in the United States. They can be set up in a short time, and require little maintenance. They are excellent for removing soluble compounds with high volatility, e.g. BTEX at concentrations of up to 10,000 ug/L. The process appears to be insensitive to fluctuations in influent concentrations, and can be applied to a wide range of concentrations of dissolved contaminants. Removal efficiencies generally exceed 90%.

Disadvantages:

Air strippers are susceptible to fouling by inorganic precipitates or biological growth which clog the packing material. Once fouling has occurred, strippers have to be taken out of service and acid-washed. Pre-treatment for iron may eliminate or minimize fouling.

Concentrations of contaminants in influent groundwater influence concentrations of contaminants in off-gases and effluents. Since this approach is non-destructive, contaminants in off-gases may require treatment as explained in Chapter 4. Finally, drinking water levels are difficult to achieve with air strippers. As a result, effluents may require a polishing step with activated carbon units.

3.5.2 Steam Stripping

This developing technology is available commercially but is not as well-documented as air stripping. Compared to air stripping, steam stripping provides a higher water temperature and steam-to-water ratio which improves the efficiency of stripping. The technology is attractive at sites where surplus steam is available.

These systems are effective for halogenated and non-halogenated semi-volatile organic compounds and fuels. For compounds with low volatility at ambient temperatures, pre-heating the extracted groundwater enhances stripping.

Like air stripping, this is a non-destructive technology. Both off-gases and effluent may have to be treated. Inorganic solids, if present, may cause fouling and impair efficiency.

3.5.3 Advanced Oxidation

Advanced oxidation, a relatively new full-scale technology, destroys hydrocarbon contaminants by converting them to carbon dioxide and water.

Commercial processes use ozone and/or hydrogen peroxide, as oxidants, along with UV radiation, and sometimes a catalyst. Most systems consist of several reaction chambers with UV lamps and oxidant injectors. Retention times are around 40 minutes. An ozone unit destroys off-gases as they emerge from the treatment tank.

Because of its high effectiveness (removal efficiencies of greater than 98% reported), treated water is often discharged to groundwater, surface water or sanitary sewers.

The target compounds for advanced oxidation are halogenated volatile and semi-volatile organic compounds and pesticides. Although it can be used for non-halogenated volatile

organics and fuels, the technology is less effective for these compounds. Because the system does not produce air emissions, potential exposure is minimal.

Units of different sizes can treat 15-200 gpm. Capital costs can range from 175,000 C\$ to more than 500,000 C\$. Because of high energy and lamp replacement costs, operating costs vary from 0.15 C\$ to 10.00 C\$ per 100 gal, or 75,000 C\$ to 300,000 C\$ yearly.

Benefits:

Unlike air stripping, advanced oxidation is a destructive technology. Commercially available systems can handle high flow rates of contaminated groundwater.

Disadvantages:

Advanced oxidation systems may require a large area. In addition, these systems require skilled operators.

High costs for operating and maintaining these plants result from the high energy consumption and replacement of costly UV lamps. Performance may be influenced by fluctuations in influent concentrations, and by the presence of inorganics and naturally-occurring soil organics. Pre-treatment may also be necessary. For example, at the Gloucester landfill plant, the water is pre-treated to remove bicarbonate and to lower pH to keep iron and manganese in solution.

3.5.4 Carbon Adsorption (Liquid Phase)

According to USEPA (1993a) regulatory agencies actively support this technology which has been used at several Superfund sites. Adsorption by “activated” carbon is not a new technology, having had a long history for treating municipal, industrial and hazardous wastes.

Activated carbon is an extremely good adsorber of organic chemicals. Activated carbon is produced by heating coal or other high lignin material in the absence of oxygen. This technique produces a material which is extremely porous and has a high affinity for organic molecules. The conditions under which the activated carbon are produced determine the pore size and adsorption properties. One form of activated carbon has been calculated to have approximately 4000 m² of surface area in only 6 grams of carbon (Liptak, 1974). The carbon can be ‘re-activated’ after use by re-heating or by using chemical methods. Heating has the advantage of destroying the organic chemicals held in the carbon.

When extracted groundwater is pumped through a series of canisters containing activated carbon, dissolved organic compounds adsorb onto the carbon. Components common to most systems contain one or more canisters in series, piping and distribution components, and a backwash system. Once carbon in the canisters has been saturated with contaminants, the carbon has to be replaced or regenerated thermally. This physical, non-destructive process may achieve low levels of contaminants in effluents and is frequently used as a polishing step to reach drinking water standards.

For carbon adsorption from the liquid phase, target contaminants are halogenated and non-halogenated semi-volatile organic compounds. The technology is less effective for treating halogenated volatile organic compounds, fuel hydrocarbons, pesticides, and inorganics. The Canadian Petroleum Products Institute (CPPI, 1994) reports it is best suited for low levels of hydrocarbons (up to 1,000 ug/L), and that it achieves a 99% removal efficiency at these levels.

Carbon units can treat between 5-100 gpm. Capital costs range from \$2,500 C\$ to \$25,000 C\$, while operating costs vary from 0.25 C\$ to 3.00 C\$ / 1000 gal.

Benefits:

Carbon adsorption systems are proven, reliable and commercially available in a variety of configurations and sizes. They are compact, easy to install, and not sensitive to small fluctuations in influent concentration.

Disadvantages:

By using this non-destructive technology, contaminants are transferred from extracted groundwater to carbon. When the concentration of contaminants in the effluent exceeds a certain level, the carbon has to be replaced, and the spent carbon has to be disposed of or regenerated.

Carbon filters will be exhausted prematurely if dissolved compounds or ions compete for sorption sites on the carbon, or if these units are used as the primary treatment for water with high levels of contaminants. In both situations, higher treatment costs will result.

Biological matter and metals can foul carbon filters and cause poor performance.

3.5.5 Bioreactors

This well-developed technology has been used for many years to treat municipal wastewater. As a result, equipment and materials are readily available.

Bioreactors are designed to bring contaminants dissolved in extracted groundwater into contact with micro-organisms which may be suspended or attached to a medium. The process is classified as suspended growth systems (e.g. activated sludge processes), or fixed film reactors (e.g. trickling filters or rotating biological contactors). Attached and suspended systems are often used together.

In suspended growth systems, contaminated groundwater and a microbial population present in activated sludge are mixed in an aeration basin. The micro-organisms degrade the contaminants aerobically, and produce new cells at the same time. In fixed film (attached growth systems) such as trickling filters and rotating biological contactors (RBCs), the microorganisms are attached to a solid medium. Common components in aerobic systems include one or more reaction chambers containing bacteria, clarifiers to remove solids and bacteria, and associated piping and distribution systems.

Bioreactors are used mainly to treat non-halogenated volatile and semi-volatile organics and fuel compounds. According to CPPI (1994), this technology is best used for lower molecular weight, highly soluble compounds such as aromatics at Total Organic Carbon (TOC) levels of < 5,000 mg/L. At these levels, removal efficiency can be greater than 99%. Factors such as temperature, concentration of the contaminant, nutrient levels, and residence time influence how the technology performs. Treated water is discharged to sanitary sewers, or may require polishing to achieve drinking water standards.

Bioreactors can treat between 5-100 gpm. Capital costs range from 15,000 C\$ to greater than 100,000 C\$. Operating costs are determined by design factors, influent concentration and desired removal efficiency. Cost can vary from 0.25 C\$ to 1.00 C\$/1000 gal. Biological treatment is often more economical than carbon adsorption (USEPA, 1993a).

Benefits:

This proven technology is commercially available, easy to operate, and destroys contaminants.

Disadvantages:

Sludge may have to be treated or disposed of. Iron precipitates may clog treatment systems therefore, pre-treatment may be necessary to remove this and other metals. Mixing required for the activated sludge process may cause volatile contaminants to be lost to the atmosphere. If this happens, emissions will have to be treated or controlled. Low temperatures will decrease biodegradation rates and result in longer cleanup times. If heating is required, costs would increase accordingly.

3.5.6 Membrane Separation

Reverse osmosis (RO) and ultrafiltration (UF) are used industrially for applications such as desalination and have recently been used to treat waste streams containing organic compounds.

This technology is based on physical processes and involves applying pressure across a membrane to separate dissolved contaminants from an aqueous phase. RO and UF use pressures of 100-250 psi and 5-100 psi respectively. Polymers and cellulose acetate are used to make membranes which are designed as tubes, hollow fibers and spirals. Membranes are commonly available as packaged units, but they can also be custom designed.

Membrane treatments are non-destructive, and produce concentrated waste streams which have to be removed and disposed. Treated effluents are normally discharged to sanitary sewers.

These technologies are best for treating water containing low levels (<5,000 ug/L) of dissolved volatile and semi-volatile hydrocarbons. UF is best suited to compounds with molecular weights greater than 1000 g/mole, while RO works best when the molecular weight exceeds 200 g/mole.

Membrane units can treat 1-100 gpm. Capital costs range from 5,000 C\$ to 100,000 C\$. Annual operating costs for electricity, as well as replacing and cleaning the membrane can be around 10%-30% of the capital cost. Disposing of concentrated waste adds to these costs.

Benefits:

In addition to removing organic contaminants from liquid waste streams, membranes also remove inorganic constituents.

Disadvantages:

Groundwater pre-treatment may be required to deal with biological fouling, hardness, and iron which may lower a membrane's performance. Temperature and varying influent concentrations may influence efficiency. In addition, because the technology is non-destructive, a large volume of concentrated waste (around 10-25% of the influent) is generated.

3.5.7 Technologies Commonly Used To Remove Organic Contaminants From Extracted Groundwater

Air stripping and carbon adsorption (aqueous phase) are the most common techniques employed for treating extracted groundwater containing dissolved volatile organic compounds (VOCs) (USEPA, 1987).

Air strippers are often selected over carbon adsorbers because of their lower operating cost. In 1987, air stripping cost 2-30 cents U.S./1000 gallons while carbon adsorption cost 20-90 cents U.S./1000 gallons. Air strippers retain these lower costs, even with the additional expense associated with the control of air emissions. Also, when the clean-up period exceeds two years, air strippers and associated emission controls are cheaper.

While economics favour air stripping, carbon adsorption may be better suited for its ability to maintain effluent quality despite flow variations and changes in contaminant concentrations and mixtures. Also, air stripping is non-destructive while spent carbon from adsorbers can be thermally regenerated, ensuring destruction of contaminants. Finally, for short periods of operation (< 2 years), carbon adsorbers are much cheaper than air strippers.

3.6 Groundwater Treatment for Dissolved Inorganic Contaminants

Inorganic compounds dissolved in groundwater are removed by techniques such as oxidation/reduction, adsorption, membrane separation, ion exchange, precipitation, coagulation/flocculation, and filtration. These techniques target inorganic constituents such as heavy metals (e.g., cadmium, copper, lead, mercury), nitrates, total dissolved solids, as well as high and low pH.

Leachate from landfills and abandoned mines are probably the major source of heavy-metal contamination while agriculture results in contamination by nitrates and total dissolved solids.

3.6.1 Oxidation / Reduction

Oxidation is often used to remove iron dissolved in groundwater. At pHs between 7.0 and 7.5, ferrous iron is easily oxidized to insoluble ferric iron. As mentioned in the section on pre-treatment (3.4), the water can simply be aerated to convert the ferrous iron to ferric iron. Iron is not a toxic metal but is considered to be a nuisance inorganic because of its negative impact on some systems used to remove other constituents from extracted groundwater.

Unlike iron, hexavalent chromium is a toxic heavy metal. Like ferrous iron, it is soluble in water at high pHs. Treatment takes advantage of the fact that trivalent chromium is not soluble at high pHs, and consists of first lowering the pH of contaminated water to below 3.0. Next, a chemical reducing agent like sulphur dioxide converts the hexavalent chromium to the trivalent

form. When the pH is raised again, the trivalent chromium precipitates. Chemical reduction is also used to remove lead and mercury.

Oxidation and reduction can be carried out using simple, available equipment and reagents. Capital and operating costs are low and the process is easy to implement. Capital costs for oxidation and reduction include costs for storing chemicals, mixing chemicals and feeding them into the treatment system.

3.6.2 Adsorption

Activated carbon adsorption, a well developed technology which is used widely for removing mixed organic compounds from extracted groundwater has already been described in section 3.5.4. In addition to removing organics, the carbon has an excellent potential to adsorb some metals like arsenic, chromium, tin, mercury and silver.

Most of the earlier comments on using this technique for organics apply to removing inorganics as well. The biggest limitation is the high capital and operating cost noted before.

3.6.3 Membrane Separation

Membrane technology, used to separate organic contaminants from extracted groundwater, may be applied to inorganic contaminants as well. Reverse osmosis (RO) requires high pressures to force pure water through the membranes, and prevent inorganics from penetrating.

Membranes can reject between 50% to 99% of the dissolved organics. A series of these membranes can be used to achieve the desired efficiency of removal. In waters containing low molecular weight organics and inorganic contaminants, the organics will pass through the membrane, leaving the inorganics on the influent side of the membrane.

This application works best when it is used primarily to polish low flow streams containing highly toxic constituents. Excellent removal is achieved for charged anions and cations, but multivalent ions are treated more effectively than univalent ions.

Water may have to be pre-treated to remove constituents which may attack the membrane or impair its performance. Pre-treatment will include removing oxidizing iron and manganese salts, filtering out precipitates, adjusting the pH to 4.0 -7.5, or removing oil and grease which may form films.

As mentioned before, these systems are readily available. They require high pressures and are expensive to operate. Capital costs are incurred for buildings, tanks, piping, membranes, flow meters, etc. Operation and maintenance include electricity for the high pressure pumps, building utilities, periodic repair, and membrane replacement around every three years. In addition, pre-treatment costs have to be taken into account.

3.6.4 Ion Exchange

Ion exchange systems rely on the process of exchanging harmful positive and negative ions in solution for harmless ions on a solid phase exchange material. This technique has a wide application in domestic water softeners which contain synthetic resin beads as the exchange material.

Table 3.3 compares the selectivity of various types of ion exchange resins. Exchangers with negatively-charged sites (acid resins) are cation exchangers because they take up positively-charged ions. The positively-charged sites on anion exchangers (base resins) take up negative ions.

In general, these resins have a higher affinity for divalent ions. Divalent ions are those ions which can donate or accept two electrons (ie. they have a charge of either +2 or -2). Divalent calcium in solution will replace monovalent sodium on a resin. This explains how water softeners work. The calcium ion which causes hardness exchanges with sodium on the exchanger in the softener. By losing calcium, the water becomes "soft".

RESIN	SELECTIVITY ^b
Strong acid	Li ⁺ , H ⁺ , Na ⁺ , NH ₄ ⁺ , K ⁺ , Rb ⁺ , Cs ⁺ , Mg ²⁺ , Zn ²⁺ , Cu ²⁺ , Ca ²⁺ , Pb ²⁺
Weak acid	Na ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺ , Cu ²⁺ , H ⁺
Strong base	F ⁻ , OH ⁻ , H ₂ PO ₄ ⁻ , HCO ₃ ⁻ , Cl ⁻ , NO ₂ ⁻ , HSO ₃ ⁻ , CN ⁻ , Br ⁻ , NO ₃ ⁻ , HSO ₄ ⁻ , I ⁻
Weak base	F ⁻ , Cl ⁻ , Br ⁻ , I ⁻ , PO ₄ ³⁻ , NO ₃ ⁻ , CrO ₄ ²⁻ , SO ₄ ²⁻ , OH ⁻

^a Source: Adapted from Paterson, J. W. "Wastewater Treatment Technology." Ann Arbor, Mich.: Ann Arbor Science, 1978.

^b Increasing selectivity left to right.

Table 3.3 Ion Exchange and Resin Selectivity^a

Plant Capacity (gpm)	Construction Cost (\$)*	Operation and Maintenance Costs (\$/year)*
50	84,105	14,530
195	116,200	21,260
305	134,770	24,280
438	154,000	27,590
597	180,270	31,531

* Updated from 1979 to 1984 dollars using third quarter Marshall and Swift Index. Source: Adapted from Hansen, Gumerman, and Culp, 1979

Table 3.4 General cost data for various sizes of exchange units

Ion exchange can also be used at contaminated sites where extracted groundwater contains soluble metallic species as anions or cations. Anions commonly removed are halides, sulphates, nitrates and cyanides. The cations are mainly heavy metal species. Spent resin can be regenerated, resulting in a contaminated ion exchange regeneration solution of extracted metals which may have to be disposed of.

Table 3.4 contains costs for various sizes of ion exchange units. Construction costs assume certain design parameters (see Wagner et al., 1986). Costs are given for operation and maintenance only. Costs for regeneration were not included because they vary widely.

3.6.5 Precipitation

Increasing the pH of a solution does not cause all metals to precipitate. For example, dissolved iron in the ferrous state will not precipitate at high pHs. Removal of iron by oxidation was previously presented.

Another way to remove metals in solution is to precipitate them as sulphides or hydroxides. Normally a sulphur or hydroxide source needs to be added and the pH manipulated in order to form a precipitate. Hydroxide precipitation is the most common type due to cost considerations. Sulphides are generally less soluble than hydroxides which means they precipitate better and produce better water quality. The sulphide technique can result in very low concentrations of metals in the effluent however it is more expensive than other techniques. Precipitation as a sulphide is not usually practical unless used as a polishing step in cases where very low concentrations of metals are required.

3.6.6 Coagulation/Flocculation

In some cases dissolved species in the groundwater will not form precipitates which settle to the bottom, and other methods need to be employed to remove them from water. In addition some groundwater needs to be treated to remove suspended solids (mainly clay particles) which will not settle and are difficult to filter.

A common method to remove fine solids which will not settle naturally is to add coagulating and flocculating chemicals and then allow time for settling. By adding specialized chemicals to extracted groundwater, and in some cases by adjusting its pH, fine suspended solids can be converted into large “fluffy” agglomerations of particles called “flocs”. Under very quiescent (still) conditions these flocs will settle and produce water of a reasonable quality. The flocs can also be removed by filtration.

The principle of coagulating and flocculating is to add chemicals which cause the suspended particles to be attracted to each other by manipulating the electric charges on the particles.

Inorganic coagulants such as lime, alum and ferric chloride are used to bring the particles together. Organic high molecular weight polymers act as flocculants to achieve the same goal. For groundwater treatment systems, lime is the preferred option because it increases pH and promotes flocculation.

3.6.7 Filtration

Filtration involves forcing a fluid through a porous medium with an effective pore size less than the size of the particles which need to be removed. Quite simply the liquid flows through the media but the particles do not and are trapped in the filter. Extracted groundwater is usually filtered by a system containing granular media. In a typical filtration bed, the filter media consists of a bed of sand, or sand and anthracite coal. Some filter systems use thin screen type filters made of paper, metal or plastic mesh or peat moss.

As water, laden with solids, passes through the media, the particles are trapped on the top of or within the filter material. A drain beneath the filter bed collects filtered liquid.

Deposition of solids in the filter may reduce the filtration rate or require higher pressures to force liquids through the media. To prevent plugging, the system is backflushed at a high velocity to dislodge accumulated particles. The backflush water and solids may require further treatment.

These filters are reported to operate economically when extracted water contains less than 100 to 200 mg/L of suspended solids. They are used after a sedimentation step to reduce the loads on the filter media. As noted earlier, filtration is applied ahead of biological systems to lessen the input of suspended solids. Likewise, when placed ahead of activated carbon adsorbers, the filters will minimize plugging in the carbon columns.

Filtration is reliable and effective for low levels of solids in extracted groundwater. Equipment is relatively simple and it is readily available, as well as easy to operate and control. Because it is easily incorporated into other treatment trains, it is a common pre-treatment process .

3.6.8 Technologies Commonly Used To Remove Inorganic Contaminants From Extracted Groundwater

Adsorption by ion exchange, and precipitation/sedimentation or filtration are the most common techniques to treat extracted groundwater containing inorganic constituents.

Before choosing a technology to remove dissolved contaminants in water, one should determine what clean-up standards will have to be achieved and how treated water will be handled. Most of the water treatment technologies can achieve standards for discharge to a sanitary sewer. However, to achieve a stricter standard, e.g. for drinking water quality, a polishing step with carbon adsorbers may be required. This additional step adds to treatment costs.

Treatability studies should be done to provide important information for choosing a treatment technology. These studies indicate if pre-treatment is necessary and which technology is the most appropriate. They also identify the best technology for removing dissolved contaminants from the groundwater being examined, as well as ways to improve how these technologies perform.

3.7 Summary

Pump-and-treat technologies involve pumping contaminated groundwater to the surface for treatment. This chapter dealt with technologies for treating pumped groundwater.

Treatment involves first removing free products and nuisance inorganics, then applying one or more of a variety of technologies to remove organic and inorganic contaminants dissolved or suspended in the groundwater. The technologies are either destructive or non-destructive. For the latter, further treatments may be required to destroy the organic contaminants.

Treated water may be discharged to sanitary sewers, surface or ground water systems, or put through a polishing step to achieve drinking water standards.

Air strippers and carbon adsorbers (liquid phase) are reported to be the most common technologies used to treat VOCs dissolved in extracted groundwater. However, if the groundwater contains semi-volatile or non-volatile compounds, other technologies mentioned in this chapter can be used.

Adsorption by ion exchange, and precipitation / sedimentation or filtration are the most common techniques to treat extracted groundwater containing inorganic constituents.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 4: OFF-GAS TREATMENT

Off-gases, which can also be called vapour-phase emissions, may need to be treated to remove or destroy the contaminants in them. Off-gases range from emissions from groundwater and soil treatment technologies to gaseous emissions directly from the surface of soil or groundwater to gases produced from in-situ venting technologies. Despite the wide range of sources, the treatment technologies for off-gases are relatively few.

4.1 Overview

Off-gases in site remediation work are very common but often are overlooked as a waste stream or are unregulated and therefore not considered for treatment. Any vapour phase product coming directly from a site or from an activity associated with the clean-up of a site can be termed an off-gas. Off-gases usually are made up of air contaminated with volatile organics, dust, nitrous compounds, sulphur compounds, carbon dioxide, carbon monoxide and/or volatile metals. In some cases off-gases are a pure or mixed substance with little or no air present. Examples are methane gas from the biological breakdown of organic wastes, nitrogen gas from purged thermal desorbers, and incinerator flue-gases.

The sources of off-gases are numerous and sometimes unpredictable. Each site and each remediation project needs to be assessed in order to identify possible sources of off-gases. Typical sources of off-gases are:

- passive emissions directly from contaminated sites
 - * methane gas from the natural biological breakdown of organic matter
 - * sulphurous gases from the breakdown of organic matter
 - * volatile and semi-volatile organics released from the pore spaces of contaminated soil
 - * dust produced by wind action
 - * gases released from leaking storage tanks or discarded containers
- emissions from in-situ treatment activities at contaminated sites
 - * soil vacuum extraction
 - * soil heating for the volatilization of contaminants
 - * air sparging
 - * bioventing
 - * steam stripping

- emissions from excavation and other surface activities
 - * volatile emissions from disturbed soil, sediment or wastes
 - * dust from construction equipment activities
 - * exhaust from motors and vehicles

- emissions from ex-situ groundwater treatment
 - * air strippers
 - * lagoons, equalization tanks, storage ponds and other exposed water surfaces
 - * filtration units
 - * biological treatment technologies (esp. trickling filters)
 - * aeration chambers
 - * chemical storage and mixing facilities

- emissions from ex-situ solid material treatment
 - * exposed surfaces of solid material during storage, handling and mixing
 - * incinerator flue gases
 - * purge gases from thermal desorbers
 - * bioslurry reactors
 - * landfarming
 - * curing of fixing agents in soil or sediment

The sources of off-gases can be broadly grouped into two categories: those which are emitted from pipes, stacks or vents and those which are emitted from the surface of a site, treatment technology process or water storage area. Those emissions from pipes, stacks and vents are essentially point sources and are fairly easy to control and collect if treatment is necessary. Off-gases from point sources often are emitted from a series of vents such as a gallery of soil venting wells. Usually these individual vents are connected to a header and pumped to a central treatment facility.

Off-gases emitted from surfaces are essentially non-point sources and are more difficult to control and collect. For non-point sources the off-gases can be controlled in one of two ways:

- collection of off-gases by vacuum - these techniques use air ducts placed over or near the exposed surface and a central pumping system to create a vacuum which sucks all or most of the emissions away from the exposed surface. The ducts feed either to a stack where gases are released untreated or to a treatment system. In some cases hoods are used to surround the exposed surface in order to increase collection efficiency.

- containment of off-gases by physical barriers and vacuum - in this technique the exposed surfaces or technologies are situated inside a building or tent. The building or tent has one air exhaust vent where all internal air must exit the structure. Air is extracted using a low pressure vacuum. The vacuum creates a lower air pressure inside the structure so that external air enters any cracks or holes and therefore internal air cannot escape the structure except through the collection vent. The vented air is then fed to a treatment system. In some cases (usually for temporary containment) a cover such as a tarpaulin is used with no collection system to attempt to prevent the creation of off-gases.

Numerous treatment technologies have been developed to treat off-gases. The broad categories of treatment options are depicted in Figure 4.1.

4.2 Off-gas Treatment Technologies

As stated earlier, off-gases can be treated in many different ways. In most jurisdictions certain off-gases can be vented directly to the atmosphere if they meet air emissions standards. The reader should be aware that this is an option in some cases (such as the venting of gasoline vapours) however, it will not be discussed further in this document. In addition, technologies aimed mainly at removing dust will not be discussed in detail. Dust in air streams is relatively easy to remove and technologies for doing so are well developed. These technologies are briefly described in the next sub-section.

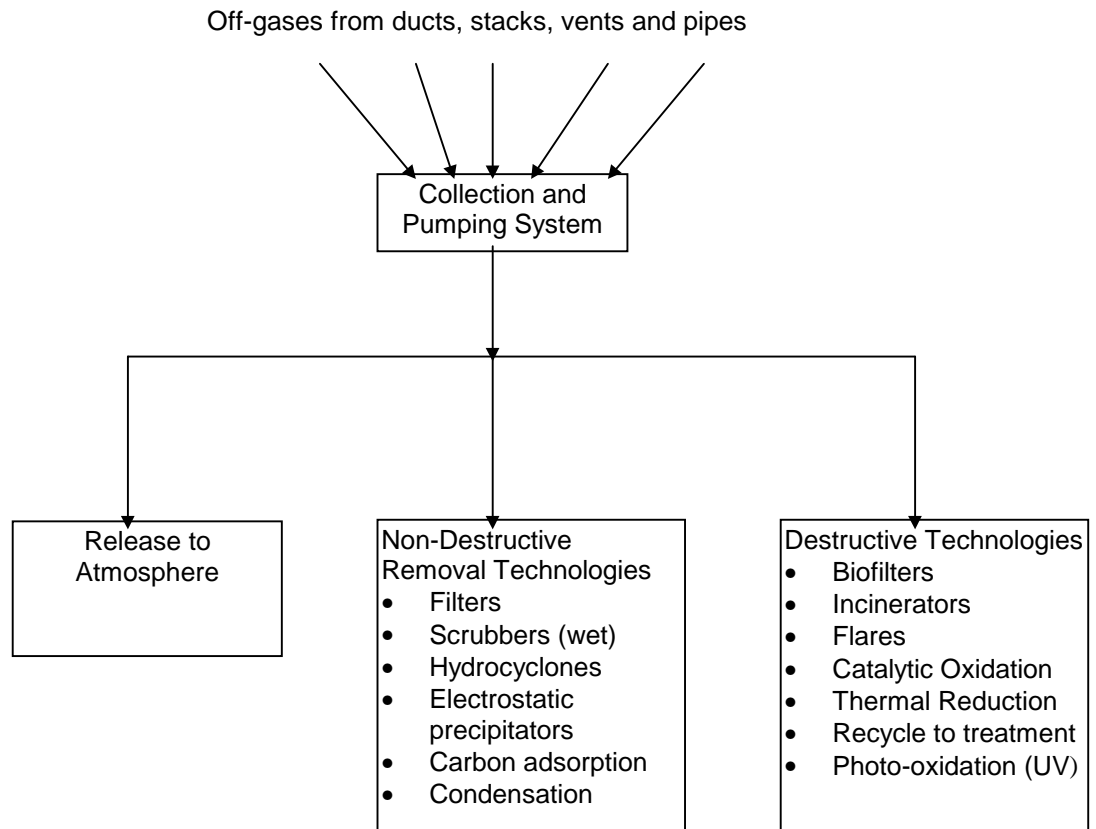


Figure 4.1 General off-gas treatment options.

4.2.1 Dust Removal Technologies

Technologies whose primary function is to remove dust and particulates are:

- **Filters** - the most common type of filter is a bag filter which is an array of cloth bags with a pre-determined pore size. Air passes through the filter but particulates larger than the pore openings do not. Other types of filters are made of mesh or fibrous materials.
- **Wet scrubbers** - these removal technologies use a spray of water or solution to remove dust from off-gases. When the dust and particulates are wetted they gain mass and fall by the force of gravity into a collection tank. Some wet scrubbers also remove gaseous components such as chlorine, sulphur compounds and nitrous compounds by spraying with a reactive solution such as caustic (NaOH).
- **Electrostatic Precipitators** - these devices apply an electric field to the off-gases. The charge imparted to the particles causes them to form conglomerates with other particles and the particles either settle or are trapped in a filter.
- **Hydrocyclones** - in these devices the off-gas is forced into the top a spiral chamber at high speed. The gas swirls downward through the chamber. The applied rotational force causes the particles to migrate to the outside of the chamber. At the bottom of the chamber the gas flow is directed upwards through the center of the chamber, however the particles are too heavy to move upwards with the gas and exit the chamber at the bottom. Hydrocyclones can be extremely efficient at particulate removal.

4.2.2 Carbon Adsorption

Carbon adsorption is the most popular choice of treatment for organic contaminants in the gas phase (US EPA, 1987). It was previously described in section 3.5.4. Adsorption is not a destructive technology; however, the contaminants trapped in the carbon are usually destroyed thermally when the carbon is removed for regeneration. Carbon adsorbers are highly effective for most organics and some inorganics. They can handle high rates of flow and are available commercially, in a wide range of sizes and capacities.

Activated carbon systems for off-gases are susceptible to fouling with water and therefore the off-gas to be treated has to be de-humidified if water content is greater than 40-50%. Carbon adsorption systems can also be fouled by biological growth, dust and inorganics. Dust is often removed before the carbon adsorption step. Biological growth can be controlled by reducing humidity or by using bactericides. Treatability studies are essential before installing carbon adsorption systems. The treatability study will determine the most effective type of carbon, the compounds which are not effectively removed and the rate at which the carbon will have to be changed.

4.2.3 Condensation

Condensation is a very common technique for treating high temperature off-gases such as those from thermal treatment systems. Condensation is a simple technique in which the off-gas is cooled to the point where the desired contaminants condense into the liquid phase and are collected as a pure or mixed liquid product. Condensation can also be used to remove excess water from an off-gas. By carefully controlling the temperature of the cooling units, different

organic products can be removed as pure products at different points in the treatment train. Cooling is achieved by compressors (ie. typical refrigeration units) or by passing the off-gas through a cold liquid or solid such as ice water. A variation on condensation is a “knock-out” trap. In these systems the off-gas is bubbled directly into water or a cold organic solvent and the contaminants enter the liquid phase as a solute.

4.2.4 Incineration

Incinerators for off-gases are well proven and effective destruction techniques for organic contaminants in the gas phase. Incinerators for gaseous contaminants are much more effective than those for liquids or solids because the distribution of heat and of contaminants inside the burner is much better. This results in more uniform and better oxidation of contaminants. Incinerators can handle high gas flow rates and still maintain destruction efficiencies over 99.99%. Incinerators can also handle fluctuations in flow rate and contaminant concentration relatively well. Incinerators of this type are proven and commercially available.

Most organic chemicals will oxidize at temperatures between 1100 - 1400 °C. The end products of complete incineration are carbon dioxide, carbon monoxide and water. Particulate matter such as dust and fly ash are usually removed from the stack of the incinerator by scrubbers and filters. Stack gas may also have to be “scrubbed” to remove sulphurous and nitrous compounds.

The disadvantages of incinerators are that they are more expensive than other systems, can produce harmful emissions if not operated properly, need regular maintenance and are not popular with environmentalists at the present time.

4.2.5 Flares

Some off-gases have a high enough energy value that they can be burned as a flare (open to the atmosphere) or in a burner unit. Off-gases may be fed to an existing flare such as found at sour gas plants, smelters or chemical factories. If off-gases are fed to an enclosed burner the energy of combustion may be recovered as heat or dynamic energy.

Not all jurisdictions allow open flaring of off-gases because they generally are not highly efficient at destroying the contaminants. Neighbors to a site where flaring is proposed will often object vigorously to the plan for obvious reasons.

4.2.6 Catalytic Oxidation

Thermal oxidation of organic contaminants may be accomplished at lower temperatures than found in incinerators by using a chemical catalyst to promote the oxidation reaction. Catalytic oxidation systems operate at temperatures of 200-500°C. The off-gases are fed to the heated reaction chamber and flow over the catalytic material, usually a metal oxide such as titanium dioxide. Oxidation of the organics occurs at the surface of the catalyst as the metal oxide releases its electron deficient oxygen.

Catalytic oxidation is an emerging technology for use in site remediation. Treatability studies need to be carried out before deciding on the use of catalytic oxidation, on the temperature of operation and the type of catalyst. It has proven useful for oxidizing fuel mixtures stripped from groundwater.

4.2.7 Thermal Reduction

Thermal reduction is, in a way, the opposite of thermal oxidation (incineration). Thermal reduction of organic molecules occurs at temperatures of 800-900 °C in the presence of hydrogen. Instead of being oxidized, as in an incinerator, organic molecules are chemically reduced. See Chapter 6 for a more complete description of thermal reduction.

Thermal reduction is available in Canada, although only through a few vendors. Its use to date has been restricted to specialty products but it has the potential for broader application. It has the advantage of being lower cost and generally produces 'cleaner' emissions than incineration.

The disadvantages of thermal reduction to date are that it is only available on a "design-built" basis, it is only competitive with carbon adsorption for certain special high strength off-gases and it may need regulatory approval in some jurisdictions.

4.2.8 Photo-oxidation

Degradation of organic molecules by light energy (mainly ultraviolet light) is well documented and in use for the treatment and disinfection of water and groundwater. Photo-oxidation of organics in the gas-phase is still in the experimental stages however. In the gas phase the problem with this technique has been that the destruction is not uniform due to uneven contaminant distribution in the off-gas and fluctuations in gas flowrate. Research is under way at this time to mitigate these problems. Photo-oxidation may emerge as a new treatment for off-gases in the future.

4.2.9 Biofilters

Biofilters are a relatively recent development in the treatment of off-gases. Biofilters for gases are the equivalent of trickling filter biological systems for water treatment. The off-gas is passed through a bed of porous material which hosts an active population of micro-organisms. As the contaminants come in contact with the media they are adsorbed and then metabolized by the organisms. Thus, biofilters are a destructive technique. Biofilters typically cannot achieve the same destruction efficiency as thermal systems, however, in many cases they can reduce the contaminant levels to below the regulatory criteria. They are inexpensive to purchase and maintain.

Biofilters are usually made of some type of metal or plastic container filled with an organic media such as peat moss, compost or wood chips. Micro-organisms are introduced into the media and conditions are maintained inside the reactor which are conducive to microbial growth. The micro-organisms are exposed to the contaminants of interest either before or after inoculation of the media. Inoculation is the process of introducing micro-organisms into the media.

A period of acclimation follows which allows the microbes to adapt to feeding on the contaminants of concern before the biofilter begins treating the gases. The off-gas is then passed through the filter under pressure. Often the off-gas has to be humidified in order to keep the media at an appropriate moisture level.

There are several disadvantages to biofilters. One is that they are not very responsive to changes in the mixture of contaminants in the off-gas. This is because the biological population cannot adapt quickly enough to treat new contaminants or different concentrations of contaminants. Biofilters are also susceptible to short-circuiting (the gas finds a preferential path through the media and does not stay in the reactor long enough to be treated). Biofilters are difficult to troubleshoot when problems occur because there are numerous variables which affect performance.

4.2.10 Off-gas Recycle

Off-gases from some processes are commonly recycled back into the ground or into a treatment unit in order to reduce or eliminate emissions and to re-use valuable energy or nutrients. In-situ treatments such as bioventing and bioslurping commonly recycle the off-gases. Biological treatment systems, both bioslurries and solid phase treatment, commonly recycle off-gases although oxygen or new air is usually blended in. Some thermal systems recycle off-gases to one part of the process to recover energy or to achieve higher destruction efficiency. Some treatment systems have successfully 'close-looped' the process. This means that no off-gases are released during treatment; all gases entering the system or created in the system are either destroyed or are continually recycled through the system. At some point however, the system must be shut down and some form of waste must be removed.

4.3 Considerations in the Use of Off-gas Treatment

If treatment of an off-gas is required, either by the regulator or by the site owner, the choice of treatment options should be based on a good understanding of the nature of the off-gas and comprehensive treatability studies to determine which technology will work and under what conditions.

The off-gas should be characterized with respect to:

- organic contaminants and concentrations;
- volume or expected flowrate of off-gas;
- other contaminants in the off-gas;
- temperature of off-gas;
- moisture content;
- oxygen content; and
- variability of parameters.

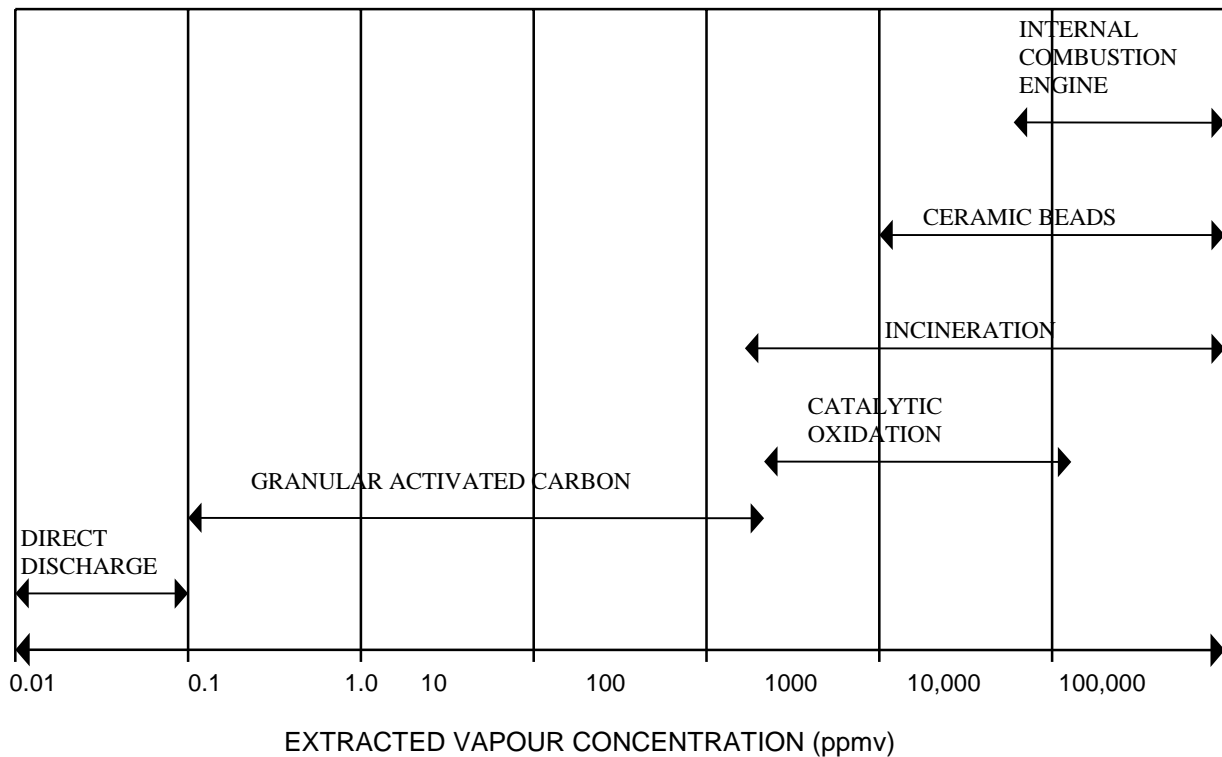


Figure 4.2 Cost-effective ranges for some off-gas treatment techniques (from US EPA 1987).

Treatability studies should determine:

- types of treatment effective on the specific off-gas;
- specific chemical or other additives required; type of catalyst; etc.;
- ideal moisture content entering treatment;
- reaction time required to achieve regulatory limits;
- costs of treatment;
- energy requirements;
- by-products expected; and
- physical specifications for treatment.

Figure 4.2 shows which types of treatment are typically chosen for various concentrations of contaminants. Figure 4.2 is taken from a 1987 document so none of the newer techniques are listed. As mentioned earlier, granular activated carbon (GAC) is commonly chosen.

4.4 Summary

Off-gases are produced as either point sources from treatment processes or as non-point sources from the surface of sites or work areas. Non-point sources are more difficult to control. Depending on the concentration of contaminants the off-gases may need treatment before discharge to the atmosphere. Contaminants in off-gases are particulates (such as dust), organic vapours, inorganic vapours, pure gases, and the products of combustion and respiration (CO, CO₂, H₂O, methane, etc.).

There are numerous technologies which can be applied to off-gases. The most common ones are technologies for particulate removal and activated carbon adsorption for organic vapour removal. Destructive technologies such as incineration, catalytic oxidation and biofilters are useful for certain situations.

As with any remedial method, treatability studies are recommended to characterize the off-gas and identify potential treatment techniques.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 5:IN-SITU CONTAINMENT

In-situ containment techniques remediate sites by preventing the spread of contamination outside of a defined boundary. In-situ containment implies that the contaminants are left in place and the containment is installed around the contaminated zone.

5.1 Overview

In-situ containment of contamination at sites is a fairly common and effective technique either as a “permanent” or temporary solution. The term containment means that contaminants are prevented from spreading outside the defined site boundary or planned containment zone. In general contaminants are not destroyed or removed with this technique although hydraulic containment does remove contaminants dissolved in groundwater. Containment can be used for excavated material as well - this is discussed in Chapter 6.

In-situ containment is the preferred solution for contaminated sites for which in-situ treatment or excavation are either impossible or prohibitively expensive. Containment is usually considered the option of last resort since no real cleanup is achieved and the site usually has severe use restrictions placed on it.

Containment options are mainly designed to contain liquid contaminants or groundwater as fluids tend to flow beyond the site boundaries. However containment is also used for soil contamination where the potential for leaching of contaminants exists or where other pathways of exposure such as airborne volatile releases exist.

The sub-options of containment are shown in Figure 5.1.

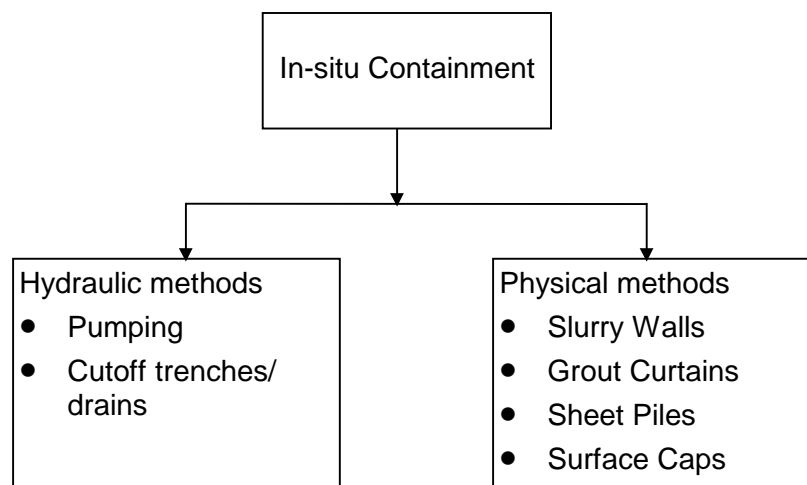


Figure 5.1 Sub-options of in-situ containment.

Containment techniques should be designed by qualified firms or individuals, on a site specific basis. This manual will not discuss the details of design but a description of each option will be given, along with some of the considerations and limitations.

5.2 Hydraulic Containment Techniques

5.2.1 Pumping

For sites with a plume of contaminated groundwater, hydraulic containment through pumping of groundwater is always an option. Pumping of groundwater contains or reduces the contaminant plume by stopping or reversing the natural flow of groundwater. The water table around each pumping well is lowered to the point where the water table in the immediate vicinity of the pumping well is lower than the water table at any other point in the contaminant plume. The groundwater then flows towards the pumping well and is extracted.

Groundwater extracted through pumping must either be treated or directly reinjected to the aquifer. If the groundwater is treated at the surface then the entire operation is called “pump and treat”. Pump and treat options were discussed in Chapter 3. Reinjection of groundwater without treatment is occasionally chosen as an option either because the groundwater does not require treatment or because the flushing action of the re-injected water is intended to clean the soil or bedrock. Figure 5.2 illustrates a specific example of hydraulic containment.

When designing for hydraulic control, the following factors should be considered:

- size of plume or contaminated property;
- groundwater flowrate and direction of flow;
- proximity of site to existing groundwater extraction wells;
- hydrogeologic conditions;
- pumping rate needed to control plume;
- positioning of extraction wells to achieve containment;
- expected height and profile of water table at steady state pumping;
- expected concentration of contaminants in pumped water (modelled over time);
- effects of re-injection of groundwater if this option is being considered; and
- environmental effects of pumping (eg. impact on water levels in nearby surface water).

The potential disadvantages of pumping systems to achieve hydraulic control are:

- hydraulic control may be required for a very long time (hundreds of years); some jurisdictions require the site owner to set up a fund which will pay the operating costs forever;
- not all aquifers are amenable to pumping;
- not all contamination systems can be contained with pumping; in some cases the plume has divided into several plumes and moved under neighboring properties and cannot be retrieved through pumping;
- pumping conditions can change over time resulting in the need to re-design the system;

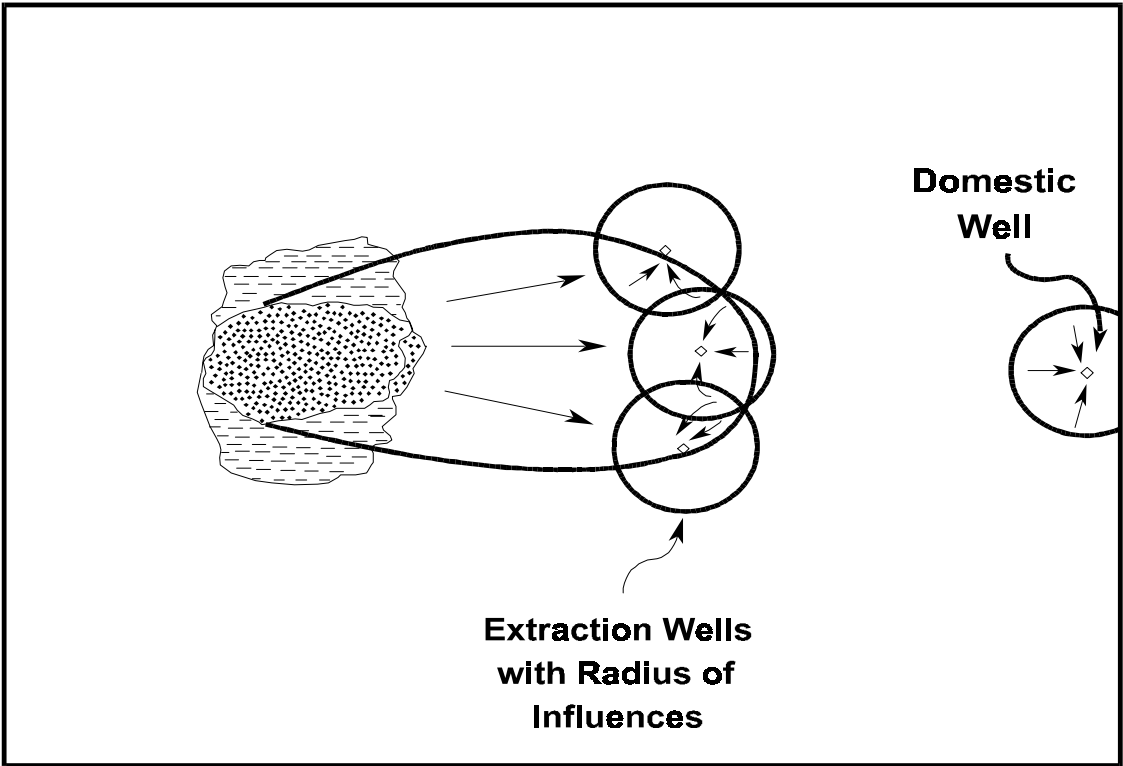
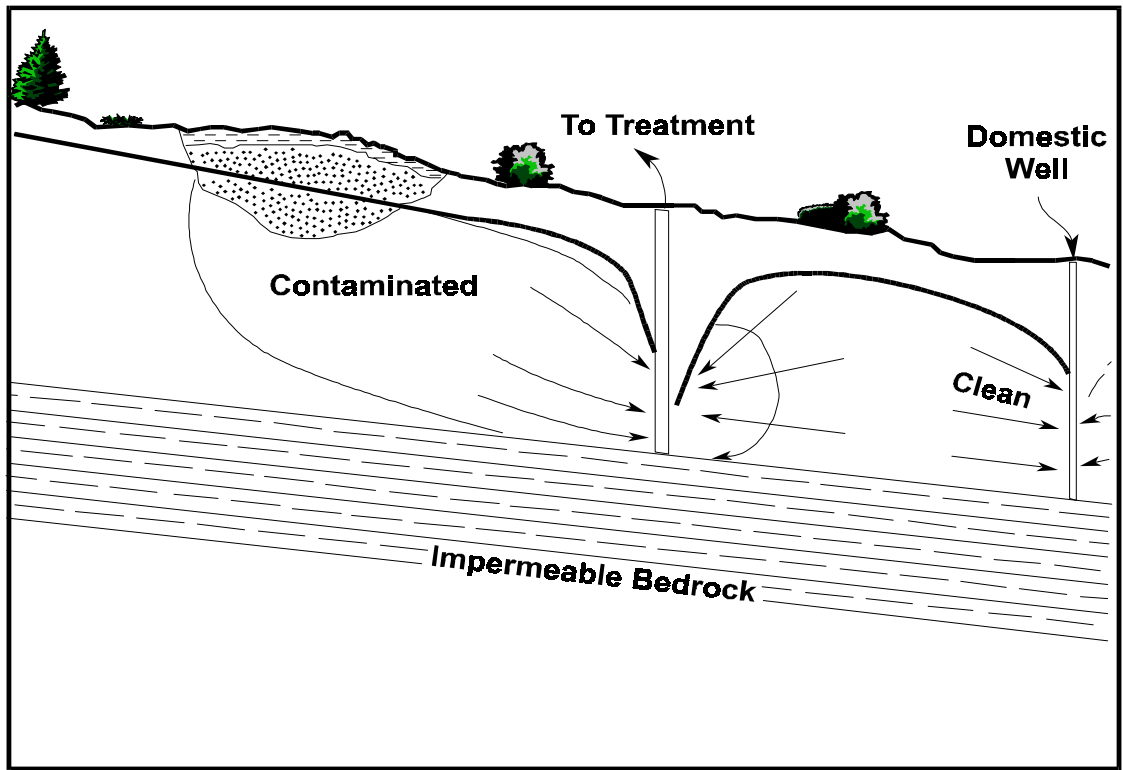


Figure 5.2 Specific example of hydraulic containment. Top - cross-sectional view. Bottom - plan view. (from Noyes Data Corp., 1985).

- not all contaminants can be treated or re-injected safely; and
- there is a high degree of uncertainty related to the effectiveness of pumping before installation because of the variability of subsurface conditions (ie. a well planned pumping system may not work as planned).

5.2.2 Cut-off Trenches and Drains

Hydraulic control of some sites can be achieved using trenches or subsurface drains to intercept groundwater flowing into or out of a site. This option is usually considered only for shallow groundwater conditions. Water entering the trench or drains flows either by gravity or by pumping to a treatment site or discharge area. Trenches and very shallow drains have the added benefit of collecting surface run-off if this is desired at the site. Trenches are often used for emergency cleanups where contamination is flowing rapidly and needs to be prevented from reaching an environmental receptor.

A cut-off trench or drain system placed upgradient of a contaminated site is designed to prevent clean groundwater from entering the site (and becoming contaminated). Also the cut-off of the flow into the site slows or ceases the flow of water out of the site since the driving force for the groundwater (the head) has been removed. Water collected in this cut-off system is usually clean and is often discharged to surface water.

A cut-off trench or drain placed downgradient of a contaminated site will collect contaminated water flowing out of the site. As with pumping systems, this water must either be treated or recycled back to the site to flush more contaminants. Some form of treatment must be available because not all water can be recycled back to the site. Since shallow water tables are heavily influenced by rainfall there will be times when the site cannot accept more water without flooding the ditches or drains. See Chapter 3 for groundwater treatment options.

Factors which must be considered when designing cut-off trenches or drains are:

- size of plume or contaminated property;
- groundwater flowrate and direction of flow; seasonal variations in flow;
- hydrogeologic conditions;
- elevation of site above or below nearby discharge points;
- positioning of trenches and drains to achieve containment;
- need for pumps and storage basins;
- expected height and profile of water table at steady state;
- expected concentration of contaminants in collected water (modeled over time);
- effects of re-injection of groundwater if this option is being considered; and
- environmental effects of drainage (eg. impact on water levels in nearby surface water).

The disadvantages of cut-off trenches and drains are:

- If used as a long-term solution, they have all the same disadvantages as pumping;
- cannot control water deeper than about 10 metres below surface;
- cannot control vertical movement of groundwater;
- trenches open to air may give off volatile emissions; and
- open trenches need special safety measures.

5.3 Physical Containment Techniques

Whereas hydraulic containment systems contain contamination by causing or allowing groundwater to flow, physical containment systems attempt to prevent groundwater from flowing out of the site.

5.3.1 Slurry Walls

Slurry walls are made by digging a trench around all, or part of, a contaminated site and filling the trench with a slurry which, when cured, forms an impermeable barrier to groundwater flow. The slurry is usually made with bentonite (a type of clay) and water. In some cases the slurry is solidified by adding soil and more bentonite and in other cases the slurry contains cementing agents so that it cures and hardens over time. The trenches must be dug either into an impermeable layer below the contaminated zone or to a point below the contamination at which the groundwater outside the walls will not mix with the water inside the walls. Sites using slurry walls are usually capped with an impermeable material to prevent infiltration of rainwater.

The considerations for use of slurry walls, grout curtains or sheet pile walls are listed in Table 5.1. A comparison of slurry walls, grout curtains, and sheet pile walls is given in Table 5.2.

5.3.2 Grout Curtains

Grout curtains are similar to slurry walls except that a slurry (the grout) is injected into the soil through drilled boreholes instead of filling a trench with slurry. Injection is achieved with a

Site Condition	Slurry Walls	Grout Curtains	Sheet Pile Walls
Depth to impermeable layer	<10 m	Any depth	<20 m (may go deeper with special equipment)
Hydrogeology	Any situation up to maximum depth.	Any situation. Grout can be injected only in key geologic formations if desired.	Any situation up to maximum depth.
Geology/ Geomorphology	Trenching difficult in bedrock and some soils.	Grout will only fill void spaces of certain soil types. Grout will increase strength of soft soils.	Driving piles not possible through rock. Very soft soils may need extra support.
Type of contamination	Must choose slurry compatible with contaminants.	Must choose grout compatible with contaminants.	Some contaminants will corrode steel. Can apply special coating on steel.
Groundwater situation after implementation	Groundwater will flow around and/or under barrier. Modelling must be done to determine paths and flowrates. In some cases groundwater will "mound" behind the barrier. Existing extraction wells may be impacted.		
Surface conditions	Must be able to bring construction equipment to site. Must have landowner permission to locate walls on property. May need surface control of site after installation.		
Surface infiltration	A cap should be used to prevent infiltration inside the barrier walls. Alternatively a system of drains under the contaminated zone can collect infiltration and pump it for treatment.		

Table 5.1 Considerations in the use of slurry walls, grout curtains and sheet pile walls. variety of different equipment and methods but all systems use high pressure to force the grout slurry into the pore spaces of the soil. Usually a standard drill rig is used to drill the holes where

the grout is to be injected. Injection is performed at numerous points around the site so that eventually an impermeable barrier or “curtain” is formed. Many different types of grout are available including bentonite, cement, silicates, ligneous materials and organic chemicals. Grout can be injected to a considerable depth and can be selectively injected to only a certain depth if this is desirable (see Tables 5.1 and 5.2 for comparisons between techniques).

5.3.3 Sheet Pile Walls

An impermeable wall can be created by driving sheet piles into the ground around all or part of a site. Sheet piles are sections of steel plate, usually corrugated for strength, which can be driven into the ground using a pile driver. As seen in Figure 5.3, the sheets interlock at the edges so a continuous subsurface wall can be guaranteed. The small gap at the interlocking points can be filled with grout or will seal itself with fine particles over time. The sheet piles can be ordered from a steel supplier in any length however there are restrictions on the height of pile driving equipment normally available. Walls have been driven to 20 metres depth. With special equipment the depth could be increased.

Factor	Slurry Walls	Grout Curtains	Sheet Pile Walls
Cost	Cheaper than grout curtains and sheet piles for depths up to 10 m.	Cheaper than sheet piles.	Expensive especially if special driving techniques or heavy gauge steel are required.
Environmental Concerns	Slurry material must be approved by regulator.	Some grouts known to have toxicity. Must get regulator's approval.	No concerns.
Longevity	May corrode or dissolve after 30-50 years. Solidified walls may crack.	Some grouts will corrode or dissolve after 30-50 years.	May corrode under acidic conditions unless cathodic protection provided.
Effectiveness	100% effective initially if installed properly.	Difficult to measure completeness of seal. Grout may not enter all pore spaces.	100% effective if installed properly.
Depth to impermeable layer	10 m	Unlimited	20 m
Availability (ease of installation)	Trenching to about 5 m with standard construction equipment. Trenches to 10 m with specialized trenching systems with limited availability.	Limited availability. Installation often difficult even for experienced installers.	Pile drivers and steel commonly available.
Maintenance	Subsurface maintenance not possible. Must monitor to detect leaks. If leaks detected, must try to install secondary wall or excavate and re-do one section.		
Reversibility	Must be excavated.	Usually not reversible.	Piles may be removed and re-used.

Table 5.2 Advantages and disadvantages of slurry walls, grout curtains and sheet pile walls.

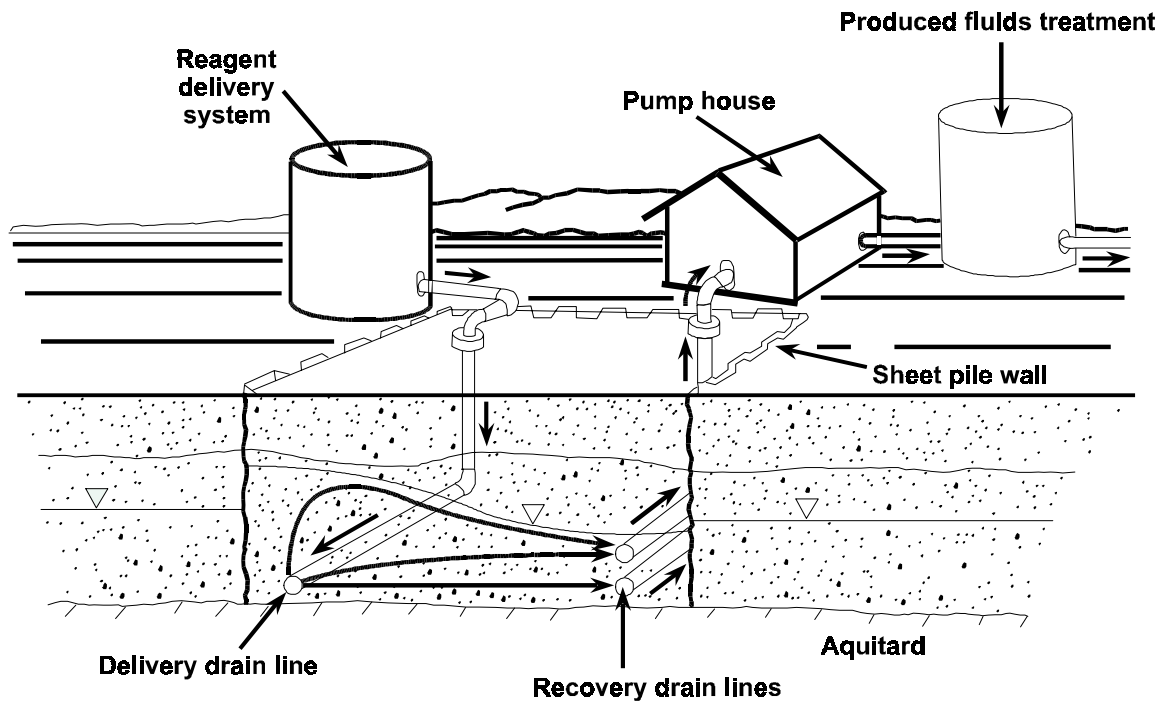


Figure 5.3 Specific example of sheet pile walls used in this case to aid in recovery of ground water (from Wastech, 1993).

5.3.4 Surface Caps

Capping is one of the most common techniques for managing sites, although it is usually used in combination with other techniques such as containment or in-situ treatment. A cap is a layer or several layers of material placed over the contaminated site. Total cap thickness is usually at least 0.5 metres and often is 1 metre or greater. The cap may be designed to be impermeable, semi-permeable, permeable to specific substances only or permeable. The permeability of the cap is dictated by the other control or treatment mechanisms at the site, the amount of rainfall and overland flow expected, the expected exfiltration of water and vapours and the planned end-use of the site.

Impermeable caps are designed to keep all rainwater and surface water from infiltrating into the contaminated zone and also to prevent contaminants from seeping out of the site. These caps are usually made of several layers of material including one or more impermeable layers. The impermeable material is usually either compacted clay or a plastic sheet (specialty plastics made for this purpose). Other layers are geofabric, sand and topsoil. Geofabrics are used to prevent erosion or to hold another cap layer in place. Some sites need to have gas vents inserted through the cap to allow the release of vapours.

Permeable or semi-permeable caps are usually used in conjunction with an in-situ treatment system or a hydraulic containment system. These caps are made to allow a certain amount of water to infiltrate into the site or to allow off-gases to leave the site.

These caps are constructed similar to impermeable caps except the impermeable layer is omitted. In some cases a layer of reactive or soluble material such as limestone, fertilizer, fly

ash or specially formulated agents are added. Infiltration of rainwater carries the dissolved reactive material down into the ground where in-situ remediation is occurring.

Caps are relatively inexpensive and remove the threat of contaminant exposure through surface mechanisms. Most caps need to be maintained as erosion and shifting of materials under the site can damage the cap. Many caps have been employed so successfully over the last 100 years that people are not aware that a contaminated site exists beneath the surface of the ground (note however that this lack of awareness has caused problems related to exposure to contamination and land use - capped sites should always be zoned for “no development” and the potential hazards clearly posted).

5.4 Considerations When Planning to Use a Containment System

Containment techniques are very situation-specific and a great deal of site characterization and modelling work is usually necessary before selecting a technique. In some cases the modelling will show that containment will not work. Table 5.3 highlights the situations where containment, in-situ treatment, pump and treat and excavation may or may not be applicable.

5.5 Summary

In-situ containment is a very common technique for controlling releases of contaminants and is often used as an interim measure until a full remediation plan can be developed. Containment can be achieved either by installing physical barriers such as grout curtains, slurry walls, sheet

Situation	Physical Containment	Hydraulic Containment/ Pump and Treat	In-situ Treatment	Excavate soil or material
Contaminated soil, vadose zone only	Yes	No	Yes	Yes
LNAPL contaminated soil, saturated zone	Yes	Yes, but likely will not remove contaminants from soil completely	Yes	Often difficult
DNAPL contaminated soil saturated zone	Probably not	Yes, but only to contain plume, will not remove significant amounts of DNAPL	Probably not	Often difficult
Drums or tanks of wastes or products.	Yes, but not preferred	Yes but not preferred	No	Yes, preferred
Soluble contaminants in shallow aquifer	Yes	Yes	Yes	No

Situation	Physical Containment	Hydraulic Containment/ Pump and Treat	In-situ Treatment	Excavate soil or material
Soluble contaminants in deep aquifer	Difficult.	Yes	Yes but often difficult	No
Free product (liquid)	Not recommended	Yes	Difficult	Yes in some cases
Radioactives	Yes	Yes	No	Very expensive and dangerous

Table 5.3 Considerations in the use of physical containment, hydraulic containment, in-situ treatment and excavation.

piles or surface caps or by installing hydraulic control measures such as pumping wells, trenches or drains.

Pumping is the most commonly used technique because it is fairly easy to install and tends to be more effective than physical barriers. The pumping of groundwater however means that the pumped water must be either treated or discharged. Thus hydraulic containment systems need long-term operational planning and funding.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 6: EX-SITU TREATMENT OF EXCAVATED MATERIALS

This section deals mainly with the technologies available for treating contaminated soils and like materials “ex-situ”. The term “ex-situ” means that the contaminated material is excavated or removed from its location on the site either permanently or temporarily while it is treated. Ex-situ treatment can occur on the contaminated site (ie. by a mobile technology) or off-site (by mobile technology or at a fixed facility).

6.1 Overview

Before beginning a discussion on available technologies a general discussion on the types of materials requiring excavation and the general ex-situ remediation options is necessary. It is only with this understanding that treatment technologies can be discussed and compared with other options.

Physically, the materials which may need to be excavated from a site can be categorized as follows:

1. Soils, ranging from clays (fine particles) to sands (large particles) to loams (organic material); water content usually <50%;
2. Sediments, ranging from clays (fine particles) to sands (large particles) to loams (organic material); water content usually >50%;
3. Rock and aggregates (eg. excavated bedrock, gravel, rubble, slag);
4. Sludges, containing mainly industrially produced solids, chemicals and liquids;
5. Solid waste (paper, metal products, vegetable matter, glass, plastic, etc.);
6. Hazardous waste (specially regulated substances with hazardous properties); can be liquids or solids; and
7. Industrial products (transformers, barrels, oils, chemicals, fuels, pesticides, etc.).

In the following sections, the term “excavated material” will be used to mean any material which is excavated, dredged or removed from a site, unless a technique applies only to a certain subset of materials.

For many contaminated sites, excavation and ex-situ remediation of excavated material are a necessity. There are numerous reasons why excavation of material is favored over in-situ treatment but the most important reason is that excavation provides an immediate solution to the problem at the site whereas in-situ treatment takes time to implement. Most property owners, once they have decided to remediate their site, want it done quickly so that they can resume use of the land or sell it.

Once a decision has been reached to excavate or remove material, the options for remediating or disposing of the material must be evaluated. Figure 6.1 is a flowchart of all of the general options for dealing with excavated material. It can be seen in Figure 1 that all ex-situ

remediation options end with some form of disposal, whether in a landfill or as some form of fill, storage or recycle. For this reason the disposal, storage and recycle options and costs of these options are the most important factors in the decision relating to remediation of the excavated material. Disposal options are discussed in detail in the next section.

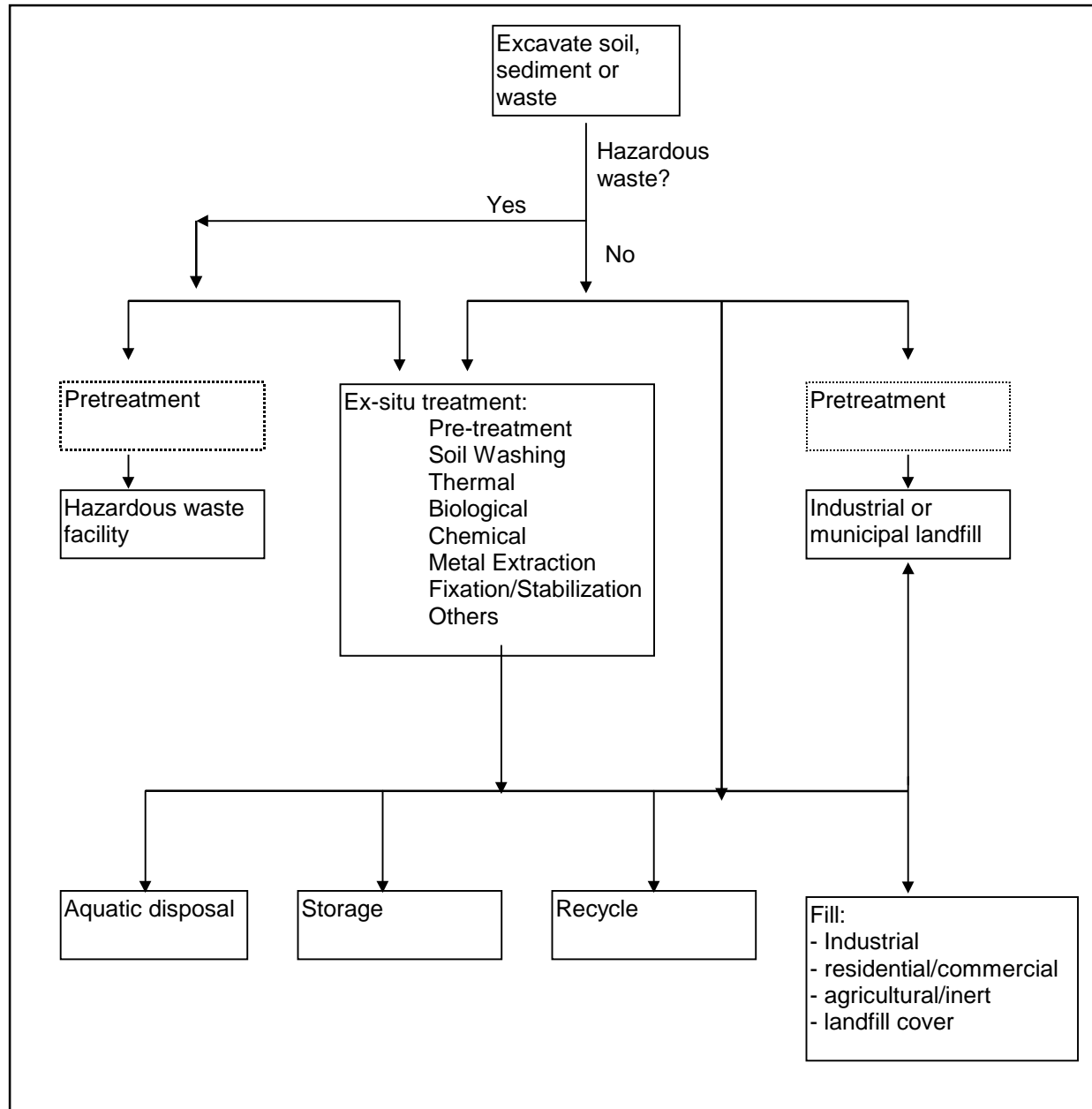


Figure 6.1 Flowchart of general options for ex-situ remediation of soil or sediment.

6.2 Disposal Options

The first thing to consider once a decision has been made to excavate materials is the choice of disposal sites, storage sites and recycling options. The choice of disposal options depends on the contaminants of concern, the geographic location of the site, the regulatory requirements for cleanup, liability issues associated with disposal sites, the desires of the site owner with respect to the excavated material, the physical state of the excavated material and the municipal zoning of the contaminated site. Once all of the disposal, storage and recycling options have been identified the regulatory criteria associated with each option should be identified. **It is important to remember that for the ex-situ remediation options, the applicable clean up criteria are those that apply to the site at which the excavated soil is disposed of.** For example, excavated material destined for a farm, as agricultural top soil, will likely have to be remediated to a more stringent level than excavated material destined for a municipal landfill (dump) site.

In some cases, disposal options do not have numeric criteria for some of the contaminants of concern. In these cases the remediation criteria must be developed using either background levels or a risk assessment approach. The background levels or risk assessment should be based on conditions at the disposal site and not at the excavation site.

6.2.1 Hazardous Waste Disposal

Certain compounds, chemicals and materials are designated hazardous, dangerous or special waste under provincial waste management regulations or under the federal Transportation of Dangerous Goods Regulations. In general a designation of hazardous (or dangerous or special) means that these wastes must be dealt with by licensed waste haulers and must be disposed of at a hazardous waste facility if disposal is the chosen option. Usually these wastes can also be treated on site using a licensed mobile treatment technology but this depends on provincial requirements. PCBs are in a special category both federally and provincially and can only be treated by licensed PCB treatment technologies or disposed of at licensed PCB facilities.

6.2.2 Industrial or Municipal Waste Disposal (Landfill)

The most common remedial option for excavated soils is disposal at a landfill. This is because of the ease of implementation and the current low cost of landfilling. Most jurisdictions separate landfills into two categories: industrial and municipal. In general for site remediation purposes landfills designated as industrial are the most important as they are licensed to receive most types of contaminated excavated material.

6.2.3 On-site Disposal/Containment

This option involves building a permanent disposal cell or landfill on the contaminated site. There are two distinct ways to achieve the objective. One is to excavate the material and place it in an engineered landfill site which is then capped. The other is to leave the material in-situ and build a barrier wall around it. This is really an in-situ technique and was covered earlier in Chapter 2. On-site disposal or containment is very popular in the United States but is used sparingly in Canada.

6.2.4 Aquatic Disposal

Most jurisdictions in Canada allow soil or sediment to be used as aquatic fill but only under very stringent conditions. The aquatic environment is generally more sensitive to chemical contaminants than the terrestrial environment therefore soil and sediment must meet more stringent criteria before it can be used as fill or disposed at sea. Federally the Ocean Dumping Regulations of the Canadian Environmental Protection Act apply to material disposed at sea. Provincial regulations or codes of practice usually deal with near-shore filling of aquatic zones.

In Ontario, for example, materials suitable for aquatic disposal or as lakefill materials must be classified as inert and meet the Ontario Open Water Disposal Guidelines, or the Ontario Fill Quality Guidelines for Lakefilling. Dredged sediments or soils to be used as lakefill material must pass the Ontario "No Effect Level" ecotoxicity criteria as described in Ontario's Sediment Quality Guidelines (1993).

6.2.5 Storage

Storage of excavated material is commonly used, as an interim measure. When a contamination situation is severe or where treatment methods have not yet been selected the project plan may call for excavation and on-site storage of materials. Storage can be on the ground surface, on an impermeable pad, inside a building or specially designed structure or in commercially available hazardous material storage container. The duration of storage is usually short (a few months); however, for some sites long-term storage is planned (eg. for storage of PCB contaminated material).

With the exception of PCBs there are no criteria for storage of excavated material. The regulatory authority would usually require a long-term plan for the site before approving a storage option. For PCB storage there are federal (CEPA) and provincial regulations.

6.2.6 Re-use/Recycle

Re-use or recycle of excavated material is an attractive option but is relatively rarely used due to the difficulty of finding a receiver for the material. The most common types of re-use and recycle are the use of soil excavated from, for example, a residential property as fill on an industrial property and the recycle of excavated free product or drummed product. Soil excavated from a residential property maybe excavated because it did not meet residential criteria but may not exceed industrial criteria and therefore be acceptable as industrial fill. Fill is discussed further in the next section. Free product or drummed product such as fuels, chemical concentrates or wood preservatives may retain all of their original properties and can be re-used either on-site or sold to another user.

There are generally no criteria or regulations governing recycling of excavated materials other than provincial waste management regulations.

6.2.7 Fill

For dredged sediment or excavated soils, reuse alternatives are usually a consideration, particularly when contaminant levels are known to be minimal, or post-treatment has reduced the concentration of contaminants to acceptable levels.

The types and level of contaminants found in the excavated material will determine whether it can be used as fill. Fill material should be protective of human health and the environment and meet any regulatory requirements.

Most soil criteria in Canada are based on 'land use'. As previously explained (in section 6.2), soil destined for agricultural use will usually have to meet more stringent criteria than soil destined as fill for a commercial/industrial property.

Most provinces, and the federal government, have adopted criteria which are similar to those developed by the Canadian Council of Ministers of the Environment (CCME). In 1991, the CCME issued the *Interim Canadian Environmental Quality Criteria for Contaminated Sites*. These numbers were intended to be interim since they did not always have the supporting scientific rationale. Since that time, the CCME has developed a science-based protocol for developing guidelines and in 1997, the CCME released the *Recommended Canadian Soil Quality Guidelines* for twenty substances.

The CCME criteria were developed for the following general land use categories:

- agricultural;
- residential/parkland;
- commercial; and
- industrial.

6.2.8 Considerations in the Use of Ex-situ Treatment

When considering ex-situ treatment as a remedial option, the project manager must first determine if excavation is preferred over in-situ treatment. Once it has been decided to excavate the material from the site, a second decision must be made to treat the material or to dispose of it without treatment. Table 6.1 provides some of the factors that should be considered when making each decision, while Table 6.2 summarizes the benefits and limitations of ex-situ treatment.

Excavation Versus In-situ Treatment When to Use Excavation	Ex-situ Treatment Versus Direct Disposal When to Use Ex-situ Treatment
<ul style="list-style-type: none"> • Property needs to be remediated quickly • In-situ treatment cannot deal with contaminants • In-situ treatment cannot deal with physical constraints • Contamination is threatening other compartments of the environment 	<ul style="list-style-type: none"> • Disposal, storage or recycle options not available • Treatability testing shows that treatment is most cost-effective • Excavated material to be re-used on site after remediation • Project Terms of Reference specify cleanup to a specific criteria

Table 6.1 Considerations when choosing excavation and ex-situ treatment.

Ex-situ Treatment Benefits	Ex-situ Treatment Limitations
<ul style="list-style-type: none"> • Meets project-specific cleanup criteria • Reduces or eliminates long-term liability • May be most cost-effective solution • May produce recyclable material or energy • Deals with problem locally 	<ul style="list-style-type: none"> • Usually more expensive than disposal • Uncertainty with many technologies as to efficiency • Usually takes more time than disposal • May need special permits

Table 6.2 Benefits and limitations of ex-situ treatment.

6.3 Treatment Options

6.3.1 General Remarks

The main goal of treatment techniques is to alter the contaminated excavated material so that it meets the criteria and goals set by the planning team, the site owner, or regulatory agencies. As stated earlier these criteria and goals relate to the planned disposal of the excavated material. In some cases another goal of treatment is to produce recyclable or re-useable material.

In the case of soils and sediments, contaminants are usually adsorbed to the solid particles of the contaminated soil or sediment. In some cases the contaminants are adsorbed preferentially to a particular type of particle in the material. Often (but not always) it is the fine particles, those less than about 40 microns (μm) in diameter, which hold the majority of the contaminants.

Usually, the strength of the adsorptive bonds makes treatment of soil and sediment difficult and very project specific. In particular, when the adsorptive bonds are strongest between the contaminants and the fine particles, a difficult situation exists because the fine particles are the most problematic to deal with physically. Other conditions in the excavated material can also have an impact on the success or failure of treatment techniques. Some of these conditions are:

- type and strength of adsorptive bonds (as discussed above);
- complexity of the matrix - most soils and sediments are very heterogeneous;
- redox potential and changes in redox potential - excavated material is usually in a reduced chemical state and then begins to oxidize after excavation;
- pH and changes in pH - especially important for leachability of metals;
- particle size distribution - clays and silts are more difficult to handle;
- agglomerations - contaminants and naturally occurring material can form complexes which are difficult to handle chemically or physically; and
- dangerous properties - makes the material hazardous to workers and the environment and requires special handling.

Good preliminary research is essential for any treatment project. The quantity, composition, and location of the excavated material have to be known accurately. Otherwise, it is impossible to make an informed decision concerning the treatment method and cost.

Often, the heterogeneity and quantity of the excavated material is greater than estimated, and this causes severe problems at the treatment site. Methods to determine the extent of contamination at the site are discussed in Chapter 7, dealing with monitoring.

In order to determine whether treatment is appropriate, a series of tests and treatment demonstrations is recommended:

- **Characterization Study** - this is a different study than the site characterization. A characterization study to determine the chemical properties of the excavated material should be performed on a composite sample of the material. The composite sample can be prepared by combining the individual core or grab samples taken during site characterization work or by collecting new material from various locations at the site. The characterization study will determine the chemical and basic physical properties of the excavated material. This includes a particle size analysis and bulk density determination.
- **Broad Treatability Study** - this laboratory evaluation will determine whether the material is treatable and, if so, what treatment methods are likely to succeed. Components of this study may include contaminant concentrations on different particle size fractions, contaminant concentration on different density fractions, settling characteristics, thermal properties, metal leachability, density at different water contents, and biological properties (including types of micro-organisms present).
- **Bench Scale Demonstrations** - once the broad treatability study has determined which treatments are likely to work, bench scale studies can be performed by selected technology vendors. Each vendor is supplied with a composite sample of the excavated material and performs their in-house tests on that sample. The project manager and the technology vendor must agree on a workplan before work starts. Some vendors will perform bench scale tests at no charge and some require payment. These bench tests should be audited by either the project manager or a specialized audit firm.
- **Pilot-Scale Demonstrations** - these on-site tests are not always necessary but should be considered especially if the technology chosen is unproven at the commercial scale. A pilot test usually lasts two to four weeks. The vendor is allowed to treat some material for a specified time in order to optimize the process. After the optimization phase, a series of audited performance runs are done. The results of the performance runs determine whether to proceed to full scale.

Treatment techniques are available for different types of contaminants in excavated material. Most techniques are still in the experimental or demonstration phase (DPTP 1992, USEPA 1994 and Wardlaw, 1995). A number of technologies have been successfully used at full scale in recent years .

Excavated material often contain various mixtures of heavy metals, petroleum hydrocarbons, and organochlorine compounds. These mixtures are difficult to treat, in general, and require two or more treatment technologies in series.

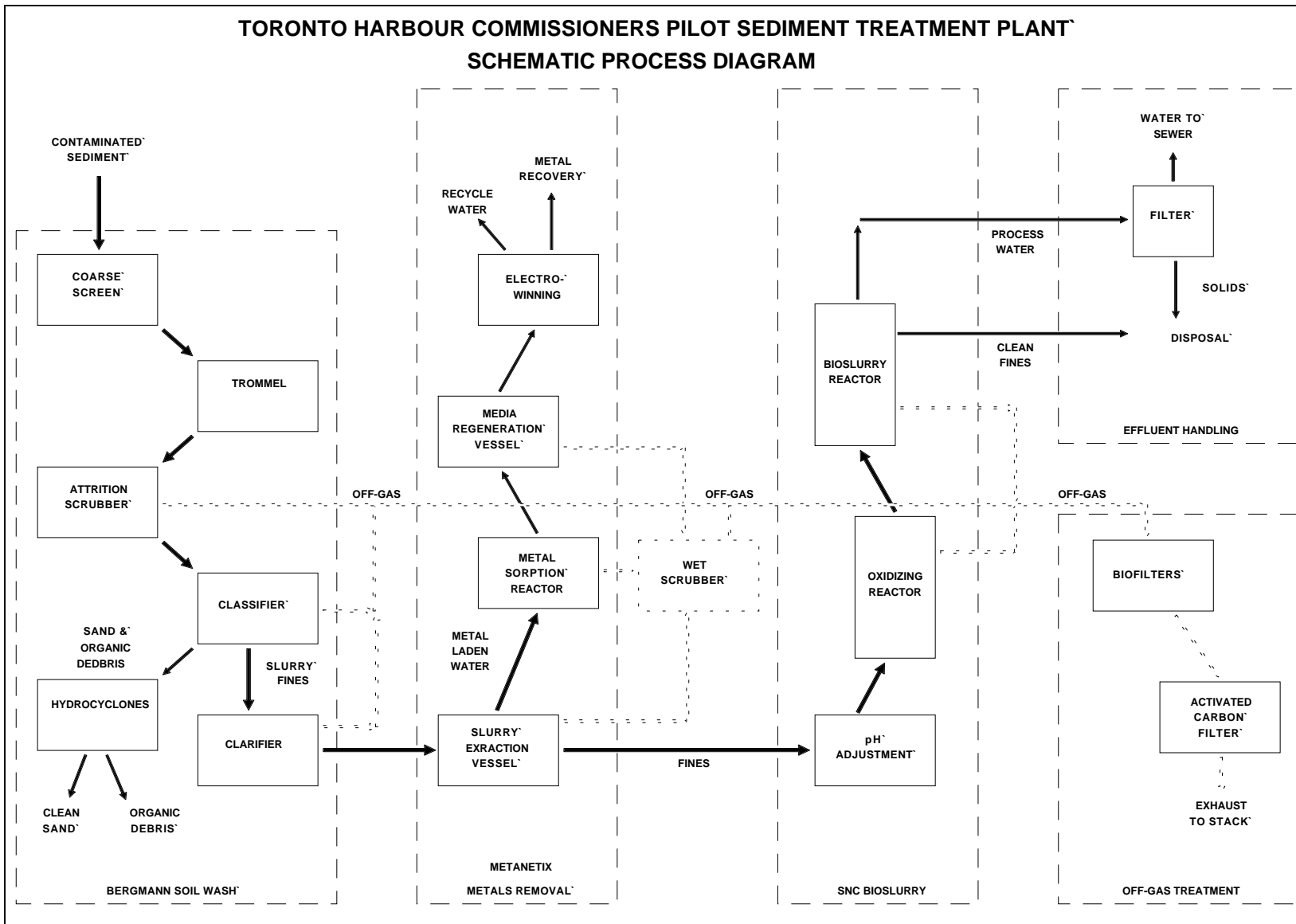


Figure 6.2 Schematic diagram of the Toronto Harbour Commissioners Pilot Plant illustrating the treatment train concept.

6.4 Treatment Technology Classes

Treatment processes can be classed as follows:

- Pre-treatment;
- Biological;
- Chemical treatment of organics;
- Metal extraction;
- Thermal; and
- Immobilization.

This classification scheme is admittedly subjective. The reader should be aware that some technologies will not fit easily into any of these categories, and others will fit in more than one category. A discussion of each follows.

6.4.1 Pre-treatment

The goal of most pre-treatment technologies is to reduce the volume of excavated material that requires further treatment or disposal and to improve the physical quality of the excavated material for further handling and treatment. Some pre-treatment techniques attempt to separate one fraction of the excavated material, which is relatively clean, from the remainder which is relatively contaminated. Others separate the water in the excavated material from the solids.

The main categories of pretreatment are:

- Dewatering;
- Size separation;
- Washing;
- Density separation;
- Magnetic separation; and
- Washwater treatment.

The first stage in handling excavated material is often dewatering. Contaminated sediments usually have a high water content, especially if hydraulic dredging is used, and it is sometimes necessary to remove some of this water before treatment or placement. Dewatering is usually accomplished with physical methods such as clarification (e.g., settling in a Confined Disposal Facility or barge, portable clarifier), “lagooning”, evaporative techniques (drying), centrifugation, or filtration. The method chosen is highly dependent on the other stages of the remediation project.

Most excavated material contains a small amount of debris, such as plant material, metal products, animal shells and bones, rocks, and aggregates of finer particles. This material is undesirable because it can damage handling and treatment systems, impede the flow of material, and carry a high contaminant load. A number of technologies have been designed specifically to deal with this material. These include coarse screens, trammels, magnetic separators, and skimmers.

One type of pretreatment is based on the fact that contaminants are often preferentially adsorbed to the smaller sized (fine) particles of excavated material. It is quite easy to separate the larger size (coarse) particles from the fines. Operational techniques are hydrocyclones and

screens. In some cases, the larger particles are washed after they are separated to further reduce the contaminant levels. Hydrocyclone separation of dredged material, in particular, plays a central role in the treatment process, especially when this is followed by a cleaning (polishing) step like flotation or a fluidized bed (upflow) classifier.

The contaminants can be found in either the heavy or light fraction of the excavated material. Some separation techniques are therefore based on separation by particle density. Technologies such as hydrocyclones, dense media settling basins, and screw classifiers are used to separate by density (or by settling rate).

Froth flotation is an advanced separation technique that is based on the chemical and physical characteristics of the contaminated sediment particles. Special frothing chemicals are added to the excavated material, and the mixture has air forced through it. The froth that forms floats the contaminants (both metals and organics) away from the solid particles. Usually the very finest particles also float with the froth and become part of the contaminated fraction.

By definition, separation techniques always produce a residue that has to be additionally treated or disposed. An important objective for separation is to minimize the amount of material to be disposed and to obtain reusable material. In many cases, separation technologies reduce the overall cost of the project.

Projects involving the dredging of contaminated sediment and projects which use water to wash the sediment or scrub the gaseous emissions often produce large quantities of excess water. In some cases, this water is contaminated and needs some form of treatment before being discharged to sewers or to receiving waters. The treatment of water is a much more developed field than the treatment of contaminated sediment. Therefore, there are a wide range of commercially available treatment options. Since most of the contamination in excess water is bound to the suspended solids, many water treatment approaches involve removing the suspended solids. This is accomplished in two ways:

- Filtration
- Enhanced settling.

Filtration systems such as sand filters, membrane filters, and bio-filters all are effective in specific situations. Settling systems include clarifiers, upflow clarifiers, and settling basins. Flocculating chemicals, added upstream of a settling tank or basin, are often effective at increasing the rate of settling. Technologies which incorporate several different unit processes to achieve separation of fractions, washing, and dewatering are called “soil washing” technologies. See the Bergmann USA schematic diagram which is part of the treatment rain illustrated in Figure 6.2.

6.4.2 Biological

Most biological treatment techniques are based on the degradation of organic substances by micro-organisms. These methods accelerate the natural decomposition of organic contaminants. They offer good prospects for excavated material that is contaminated with petroleum hydrocarbons and PAH's (Stokman and Bruggeman 1993, Wardlaw 1994).

The main types of biological treatment include:

- Solid phase
 - composting
 - "pad" farming
- Slurry systems
 - closed vessel
 - open vessel
- In situ (discussed in Chapter 2)
- Specialized
 - phytoremediation
 - biological control of redox potential to leach or immobilize metals

Landfarming systems treat the excavated material in the solid phase (less than 60 percent water), usually by spreading the excavated material in a thin layer on a pad or directly on the ground (this can be done in a CDF). Bioslurry systems treat excavated material in the liquid phase (greater than 70 percent water) in an enclosed reactor or open treatment basin, possibly a CDF. Both techniques attempt to optimize the growth conditions for micro-organisms. Nutrients, air, and additional carbon sources (food) are usually added to the excavated material.

The efficiency of biological treatment seems to be highly dependent on the form in which the pollutants are adsorbed to the sediment. A great deal of research is being directed to biological treatment, and breakthroughs in treatment efficiency are occurring rapidly (DPTP 1992).

An advantage of biological treatment is that the excavated material retains its soil-like characteristics (ie. its organic content). Thermal and chemical processes can strip soil and sediment of organic material which means the treated product is less valuable as fill.

A completely different technique is decontamination using plant cultivation. This method, also called phytoremediation, uses the capacity of various plants to collect substances (such as heavy metals) through their root system or directly through the cell walls of algae. The results depend on the soil characteristics, the mixture and concentration of contamination, and the plants' ability to absorb contaminants. Ex-situ phytoremediation is similar to in-situ phytoremediation (discussed in Chapter 2) but treats excavated material in a specially designed cell or treatment pad.

6.4.3 Chemical

Chemical treatment of contaminants in excavated material is based upon chemical-physical interactions such as adsorption/desorption, oxidation/reduction reactions, pH adjustment, and ion exchange. Chemical treatment can be broadly divided into two sub-categories: (1) those techniques that attempt to extract contaminants and (2) those that attempt to destroy or alter contaminants in the excavated material. In addition, the treatment methods for heavy metals are fundamentally different from those for organic contaminants.

The categories of chemical treatment are:

- Reactive
 - oxidizers
 - dechlorination
 - complexing
- Extraction of organics
 - organic solvent
 - water based solvent.

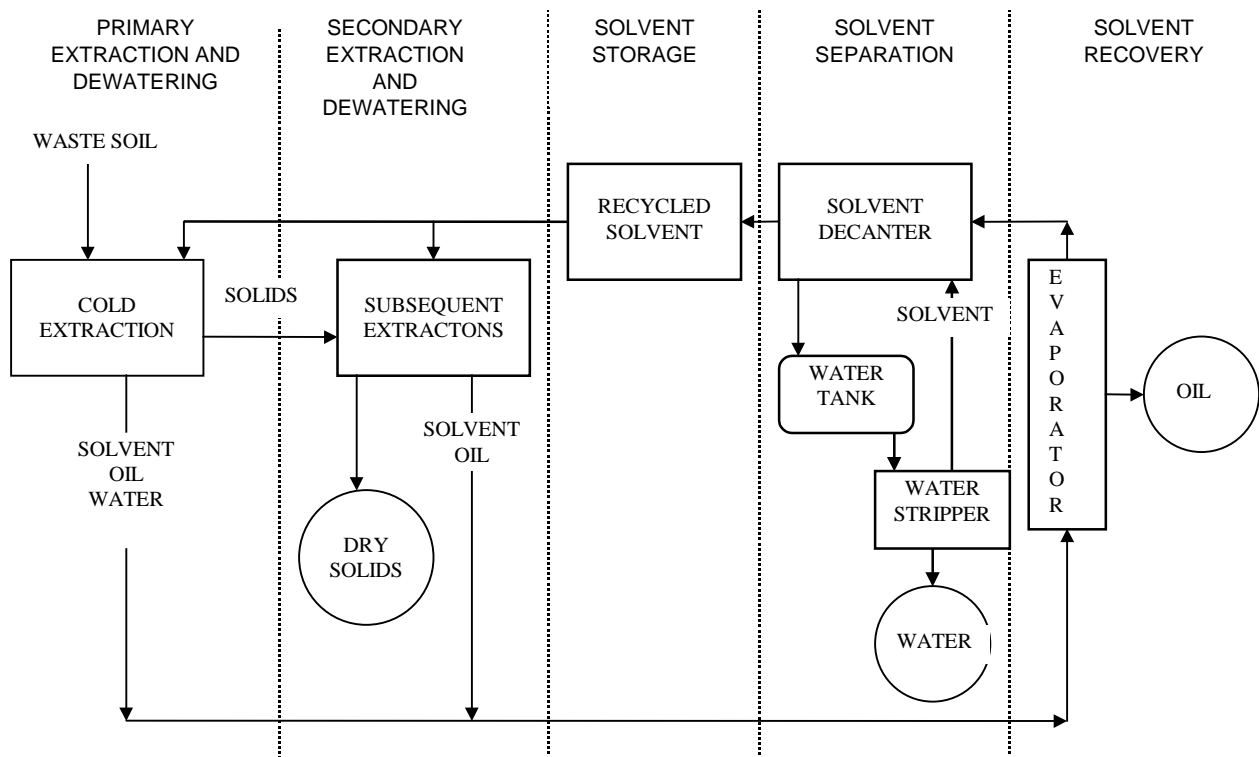


Figure 6.3 Schematic diagram of the BEST solvent extraction process (from Resources Conservation Company, 1994).

Organic contaminants in excavated material can be destroyed by the addition of a strong oxidizing agent such as hydrogen peroxide, ozone, or “wet air.” A major problem with these techniques is that the oxidizing agent is not specific to the contaminants, and a great deal of oxidizing agent is used up in the oxidation of naturally occurring organic material.

Chlorinated organic contaminants such as polychlorinated biphenyls (PCB's) can be subjected to a chemical treatment which removes the chlorine from the molecular structure. There are a variety of patented techniques, but most use an earth metal such as sodium or potassium to react with the chlorine atoms and render the organic molecules harmless.

Organic contaminants can be extracted by washing with organic solvents or with water based washing solutions. Several commercial-scale units are available for this purpose. These processes can achieve removal efficiencies better than biological treatment but not as high as thermal treatment. Figure 6.3 is a process flow diagram of a solvent washing process.

6.4.4 Metal Extraction

Unlike organic chemicals, metals cannot be destroyed. Therefore the only techniques for reducing the concentration of metals in excavated material are extractive ones. Because metals are naturally occurring and because they occur in a variety of chemical forms within the same soil, sediment or sludge, they are often quite difficult to remove. However some techniques have been developed which achieve reasonable results. The basic categories of metal extraction are:

- Leaching
 - acid solutions
 - basic solutions
 - chelating agents
- Flotation
- Electrokinetics
- Sonic Mixing
- Phytoremediation
 - uptake by macrophytes
 - enhanced leaching by sulphur respiring bacteria

Extraction of metals using acids or complexing agents may result in a considerable reduction in the heavy metal content. Acid extraction technologies are the most common since many metals are more soluble at low pH. Most technologies in this category are quite effective if the excavated material is contaminated with one or two metals but may have some problems when a mixture of metals is present. While extraction methods can remove the heavy metals from the excavated material, they are probably applicable only to very highly contaminated sites, due to high costs. Figure 6.4 illustrates the process flows of a metal extraction technology.

Flotation is a process developed originally for the mining industry, to separate metals from crushed ore. In a flotation cell the excavated material and specific froth-inducing chemical additives are mixed at high speed and air is added. Complexes of fine metal-bearing particles, chemical additives and air bubbles are formed and these float to the top of the cell where they are easily removed by skimming. The heavier, larger particles stay at the bottom of the cell (and are therefore referred to as “tailings”).

For some excavated material this is an effective treatment as the tailings will have much lower metal content than the froth. This technique is a volume reduction technique, much like soil washing.

Electrokinetic techniques use a difference in electric potential to cause metals to migrate toward either an anode or a cathode. This can be done in the solid phase or in the slurry phase. Sonic techniques use sound waves to cause the metal ions to move towards sonic nodal points. Neither technique has been commercialized to any great extent.

Removal of metals by macrophytes is a useful technique, where allowed by the regulator. Some plants have the ability to ingest metals through their root system and retain them in the cellular structure. Phytoremediation systems culture such plants in a controlled area and the excavated material is added to the area. The mature plants are then harvested for use (eg. trees are used for lumber) or disposed of. One of the problems with this technique are that animals which eat macrophytes can become contaminated with metals. The disposal of the plant material can be problematic.

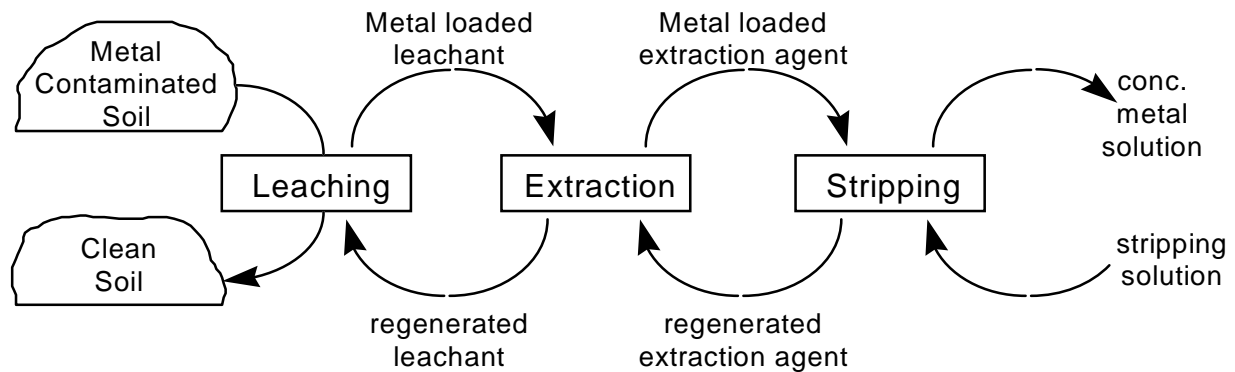


Figure 6.4 Adapted from: Process flow diagram of the Cognis Terramet metal extraction technology. (from Cognis Inc., 1993)

A number of techniques that are under development may ultimately lower the cost of metal treatment. One of these, biochemical extraction with H_2SO_4 (using microbes that produce sulfuric acid while consuming organic pollutants), has had promising results for the removal of heavy metals, except lead.

6.4.5 Thermal

Excavated materials, or the residues from other types of treatment, that are very seriously contaminated with organic material may be treated thermally. Thermal treatment techniques are often expensive, but they can achieve very high removal and destruction efficiencies.

The various types of thermal treatment can be categorized as follows:

- Desorption;
- Incineration;
- Thermal reduction; and
- Vitrification.

Thermal desorption is the application of heat to volatilize and remove the organic contaminants and mercury (mercury is a volatile metal) present in a solid matrix. The volatilized contaminants can be condensed and collected as an oily residue of substantially less volume than the original sediment mass. Although no net destruction of contaminants is effected by this technology, the remaining volume of contaminated oil requiring further treatment is much smaller, thus potentially allowing the application of other (more expensive) destructive methods. Recently, thermal desorption costs have dropped dramatically in Canada, to the point where thermal desorbers are now priced competitively with landfills and biological treatment.

Incineration is an established technique for hazardous waste, and excavated material. Incinerators destroy all of the organic matter in the excavated material by oxidation at very high temperature. Because the energy requirements for incinerators are high and air emission requirements are strict, incinerators tend to be the most expensive type of treatment.

A relatively new type of thermal treatment is thermal reduction. In this technique, temperatures as high as those used in incineration are employed but a gas other than oxygen (usually hydrogen) is present in the reactor. The result is the reduction of organic molecules into lighter and less toxic products. Chemical reduction is, in one sense, the opposite of incineration, which is an oxidative process. The advantage of these systems over incinerators is that they do not produce any harmful stack gases and they are not affected by the presence of water in the excavated material. Figure 6.5 is a schematic diagram for a thermal reduction process used in Canada.

Last in the thermal category is vitrification. This is a thermal process that is essentially a thermal desorber for the organic contaminants and mercury but also immobilizes metal. The process is run at a temperature high enough to melt the silica and metals in the excavated material. After cooling, the excavated material is thereby turned into a hard slag-like product from which the metals will not leach. Most technologies in this category produce a product such as a gravel or brick which can be used as a building material. A disadvantage of vitrification is the high energy consumption and the flue-gas emissions produced. Vitrification has rarely, if ever, been used at full scale in Canada.

6.4.6 Immobilization by Fixation or Solidification

Immobilization is a treatment method that attempts to prevent contaminants from moving out of the solid matrix of the excavated material. This is done either by chemically binding the contaminants to the solid particles (fixation) or physically preventing the contaminants from moving (solidification).

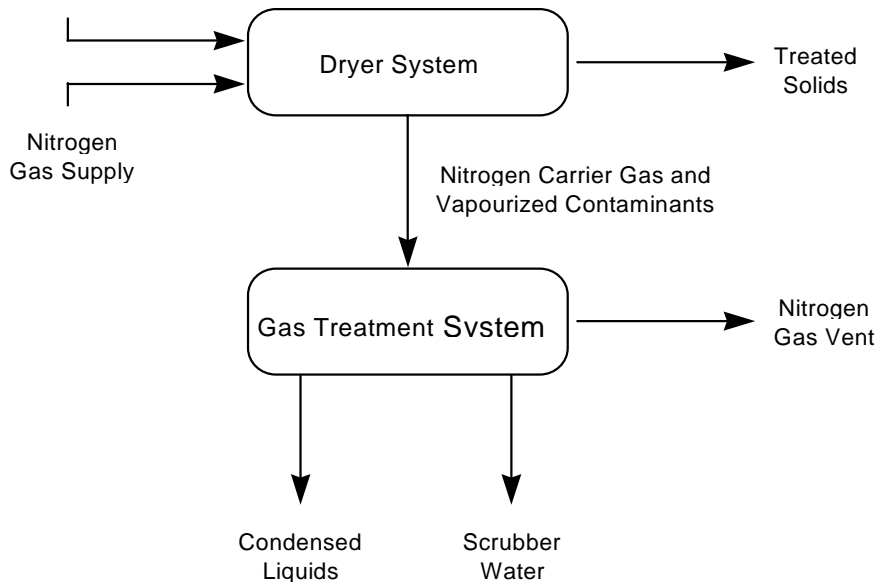


Figure 6.5 Process flow diagram of the XTRAX thermal desorber. (adapted from Chemical Waste Mgmt., 1993)

In some cases a combination of physical and chemical immobilization is used. After this type of treatment, the excavated material usually must be placed in a disposal site or used as a construction material (where allowed by law).

Fixation techniques are based on chemically fixing contaminants to prevent dispersion into the environment. There are a number of different approaches to fixation. One involves adding large quantities of hydroxyl-forming substances which raise the pH of the material and cause most of the metal species to become immobile. Another technique uses a silica solution to “encapsulate” the contaminant/particle agglomerations. This technique is not always effective especially where high levels of organic contamination exist.

Solidification of excavated material is achieved by adding a cementing substance or by high-temperature melting (see vitrification in section 2.3.4). After the addition of a cementing substance, the excavated material can be allowed to cure in a large mass in a fill site or formed into smaller blocks or bricks.

The main disadvantage of immobilization techniques, and the reason many countries do not allow immobilized excavated material to be used as construction material, is that the contaminants remain in the excavated material. It is possible that the effectiveness of the immobilization will be short term and that leaching of contaminants will occur after a number of years.

6.5 Cost Considerations of Treatment Technologies

The cost of treatment of excavated material has traditionally been perceived to be much higher than the cost of disposal. In recent years the costs of treatment have decreased as new, more effective, techniques have been developed. The cost of landfilling, which is the main alternative

to treatment, tends to vary quite dramatically between jurisdictions and based on competitive forces. At this time (1996/97) landfill costs are quite low compared to historic levels and many project managers are choosing landfills as the disposal option. However the costs of treatment are still quite competitive, therefore, for each project, the costs of all options must be carefully analyzed.

The costs of the different treatment techniques can be accurately determined only in specific situations. The factors determining the costs include:

- Degree of utilization of a treatment plant;
- Price of land;
- Type of excavated material;
- Nature and degree of pollutants;
- Required efficiency (the quality of the end product);
- Scale of utilization;
- Energy consumption;
- Consumption of raw materials (chemicals, etc.); and
- Regulations and permit requirements.

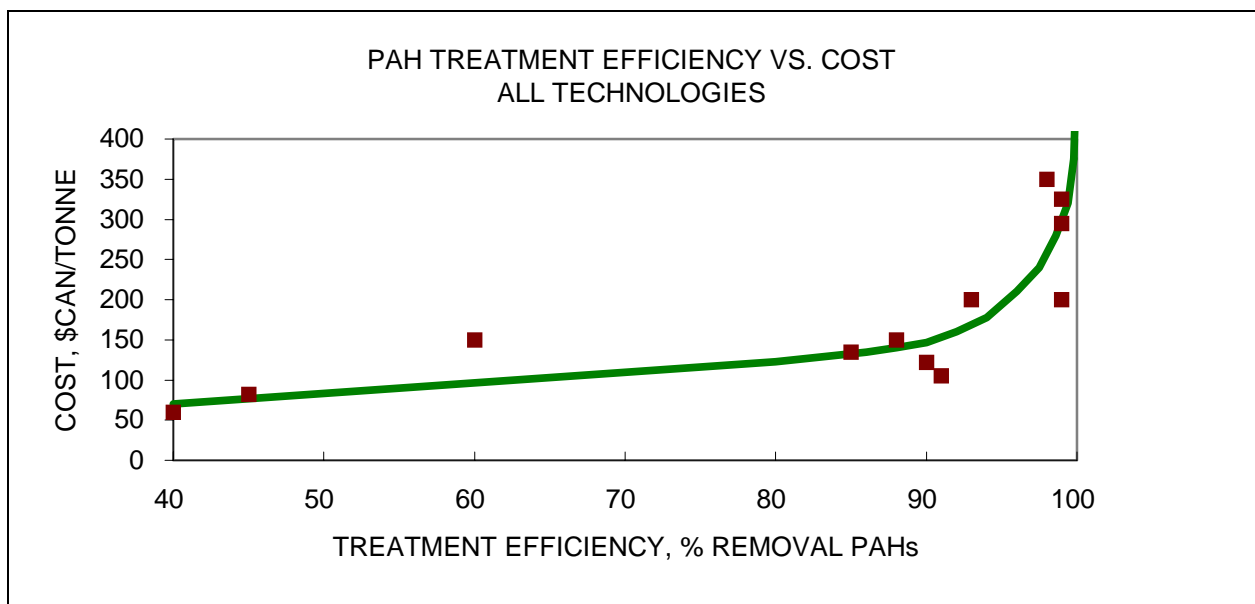


Figure 6.6 Relationship between cost and effectiveness for the treatment of PAH's in excavated material, as developed by Canada's Great Lakes Cleanup Fund (Wardlaw et al., 1995).

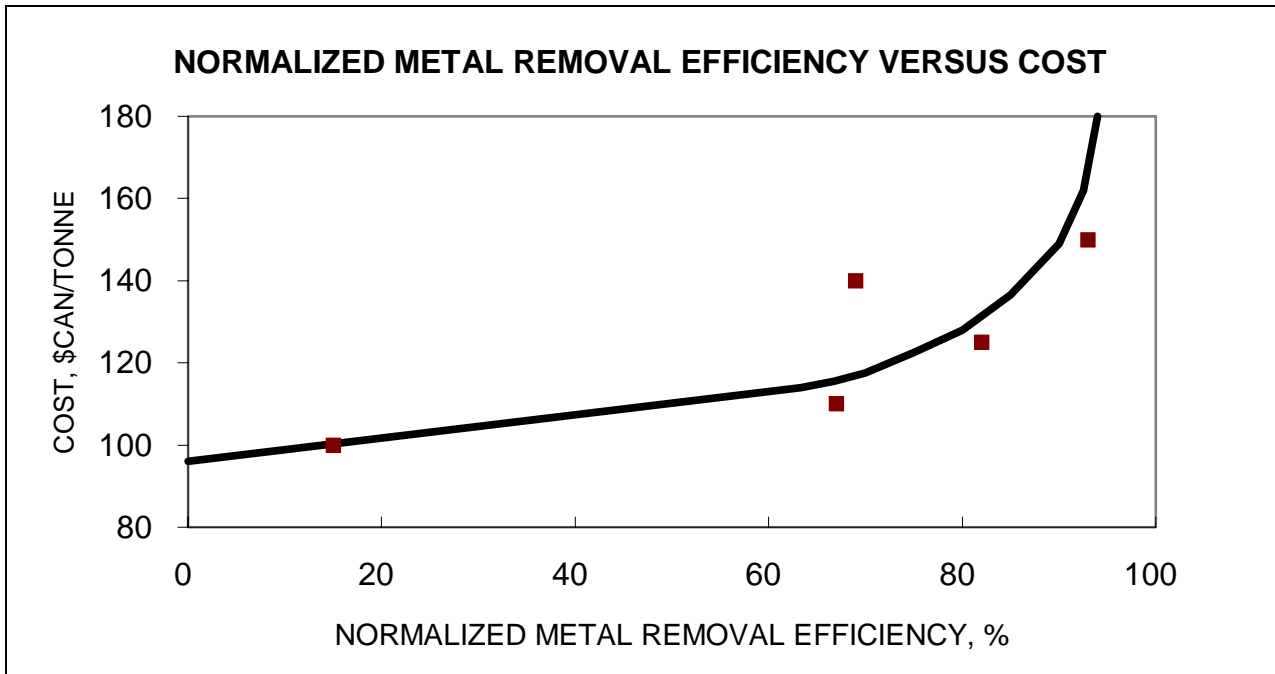


Figure 6.7 Relationship between cost and effectiveness for the treatment of metals in excavated material, as developed by Canada's Great Lakes Cleanup Fund (Wardlaw et al., 1995).

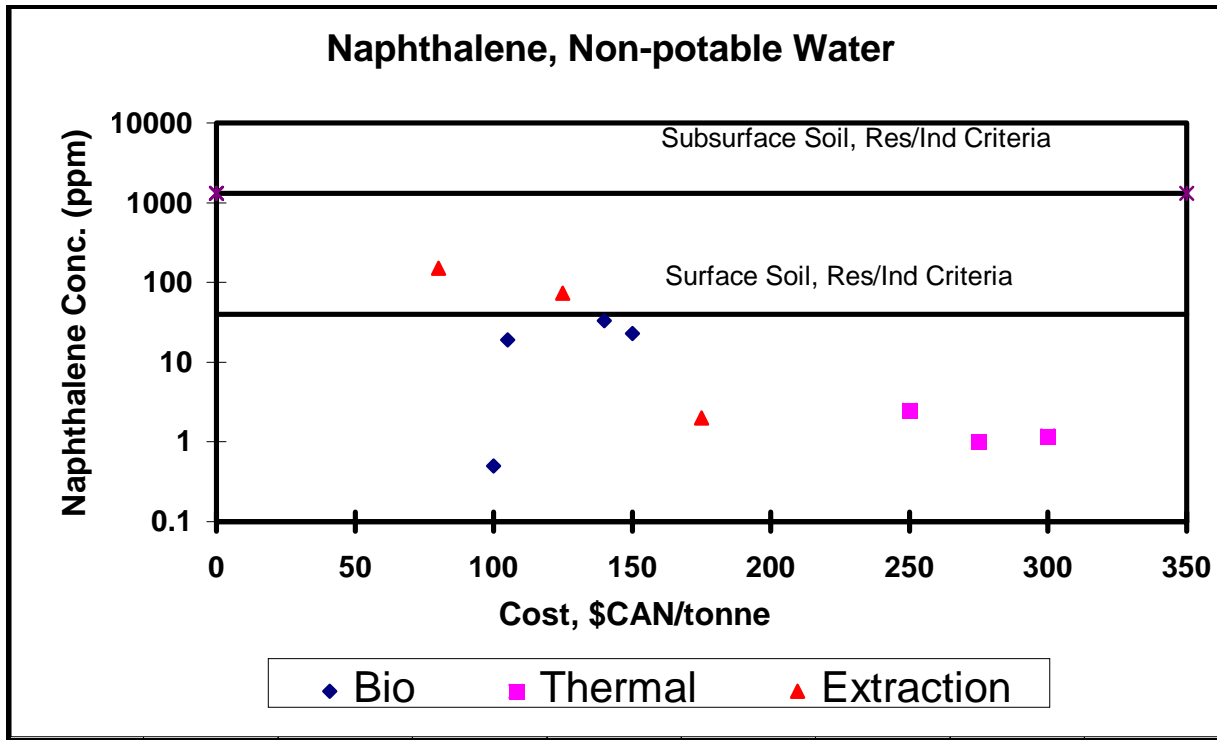


Figure 6.8 Final naphthalene levels (in treated sediment) versus cost for treatment. Also shows relevant Ontario criteria (adapted from Wardlaw et al, 1995).

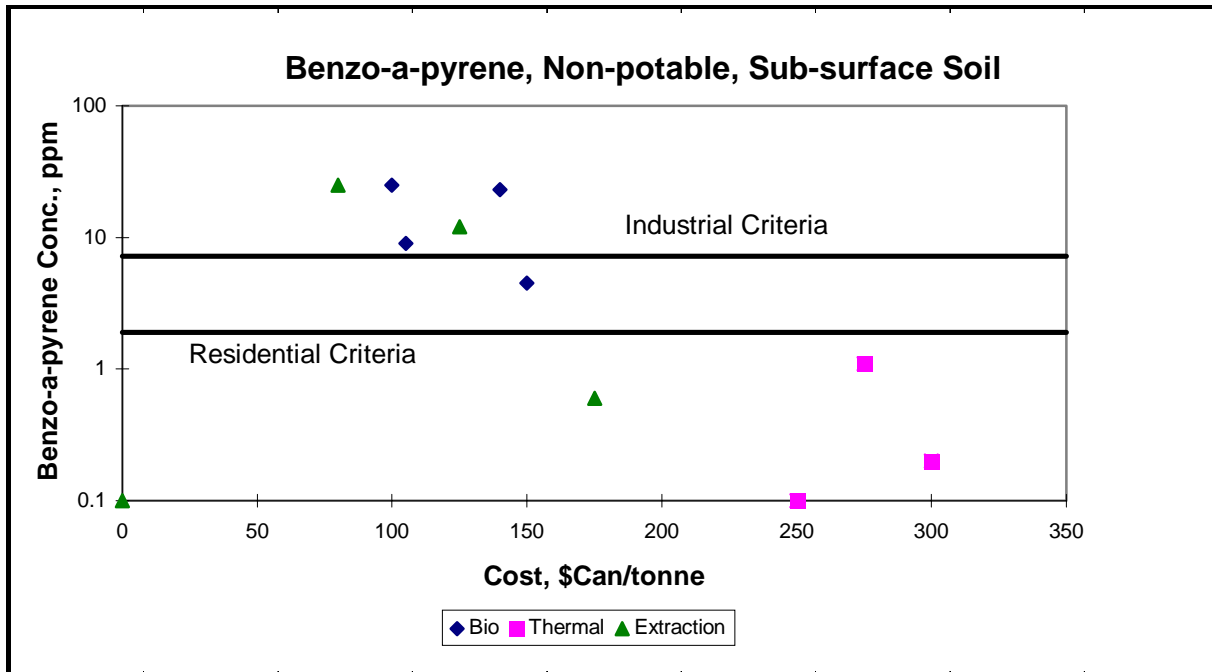


Figure 6.9 Final benzo-a-pyrene levels (in treated sediment) versus treatment cost. Also shows relevant Ontario criteria (adapted from Wardlaw et al, 1995).

It is logical to expect that costs of treatment increase with an increase in the level of treatment needed. Figures 6.6 and 6.7 illustrate the truth of this premise using actual data collected for sediment treatment technologies. Note that in these figures, the curves drawn were fitted by eye not by regression analysis. The question of cost versus effectiveness is one which every project manager will face. In particular, it is critical not to pay more for treatment than is necessary, for the level of treatment efficiency required. Figures 6.8 and 6.9 are plots of the cost of various types of treatment versus the contaminant level (naphthalene and benzo-a-pyrene) in the treated material (sediment).

6.6 Summary

A wide variety of treatment techniques are available for excavated material. The currently available technologies can destroy, remove, or immobilize all types of contaminants and are applicable to almost all types of excavated material. The treatment costs are still high compared to landfilling (in Canada), but these are decreasing.

Each project involving excavated material is a unique situation that demands a “custom-fitted” solution. For each site, the optimal combination of treatment techniques must be determined by weighing technical, economic, human health and environmental aspects.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

CHAPTER 7: PROJECT MONITORING AND POST-PROJECT MONITORING

Monitoring of a site can occur at any time before, during or after remediation activities. Monitoring which occurs before remediation begins is usually referred to as “assessment” and is not covered in this discussion. Monitoring which occurs during remediation is called project monitoring and monitoring which occurs after remediation is completed is called post-project monitoring or sometimes long-term monitoring.

Monitoring is any activity which attempts to quantify the nature and extent of contamination at the site, the effectiveness of remedial activities, emissions from the site or remedial technologies and the impacts of the contaminants on the environment or human health. Normally this involves taking some sort of sample or measurement and analyzing it or using it in a test procedure. However, monitoring also involves visual, auditory and olfactory (odour) observations.

The following are general principles pertaining to any type of monitoring:

- Plan ahead - plan all of the monitoring before the project starts. The monitoring plans should be developed soon after the remedial options are chosen and in consultation with the remedial contractors and sub-contractors.
- Use appropriate expertise - select the firms or individuals for monitoring with as much care as the remediation contractors
- Mass balance approach - where appropriate, specify that the monitoring results should allow the calculation of a mass balance for the substance(s) of interest. To perform a mass balance the mass (weight) of media and the concentration of substance in that media must be measured at all points in the process. A properly conducted mass balance is the only means to determine the true fate of a substance. See Figure 7.1 for a general description of a mass balance.
- Use independent parties for monitoring - the monitoring should be done by a party “at arm’s length” from the remediation contractor(s) or by the project manager. If the remediation contractor is chosen to perform the monitoring then have the work audited by a third party.
- Specify laboratory methods in advance - ideally laboratory methods should be identified and adhered to right from the start of site assessment activities. Often this is not possible because of discontinuities in the contractors and project managers involved in the work. However changing sampling or laboratory methods could have an enormous ($\pm 50\%$) impact on analytical results.
- Develop a Quality Assurance/Quality Control protocol - the monitoring plan should include methods to assure the quality of the monitoring results. Some of the components

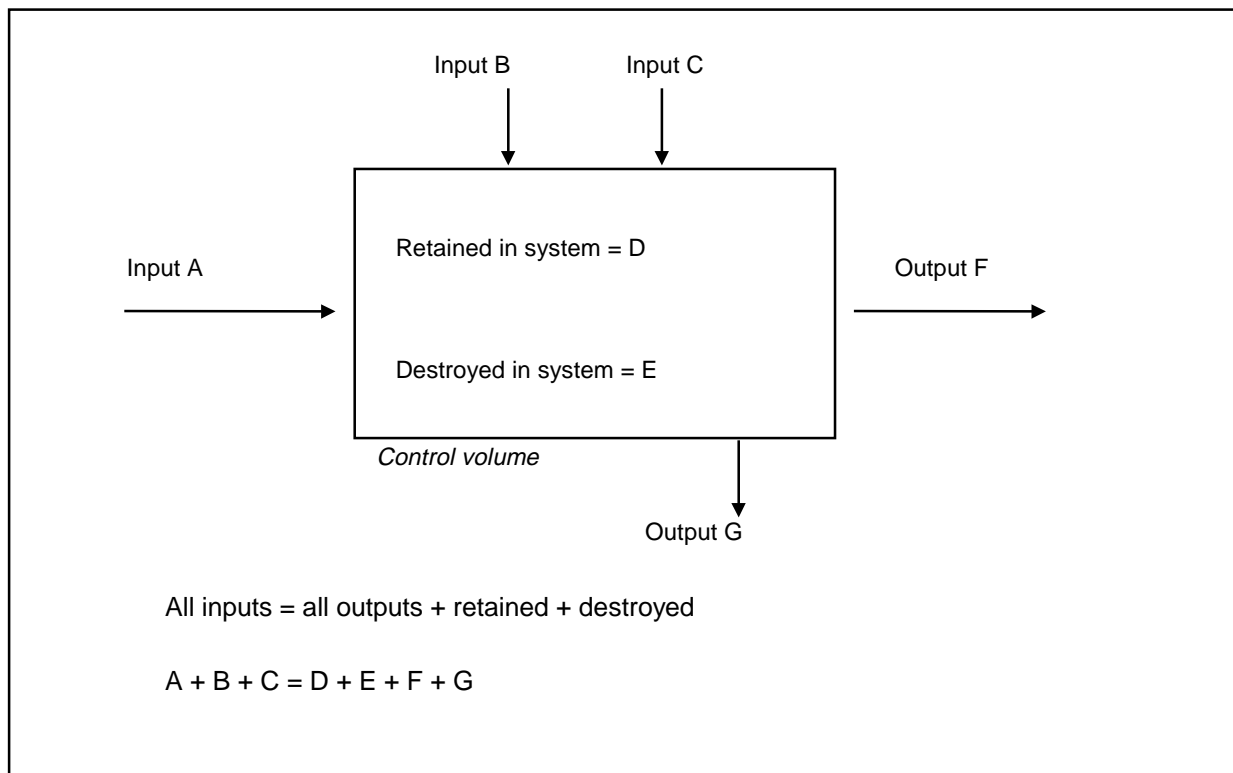


Figure 7.1 Illustration of control volume and mass balance concept. For a mass balance of a contaminant, the mass or volume and the contaminant concentration of all inputs, outputs and system components must be measured.

of a QA/QC plan are split samples, duplicate samples, replicates, statistically valid sample numbers, surrogate analysis, field blanks, trip blanks, laboratory blanks and chain-of-custody measures.

7.1 Project Monitoring

As defined earlier, project monitoring is that monitoring which occurs at the time of remediation activity. The purposes of project monitoring are to:

- Determine compliance with project plan/contracts;
- Determine effectiveness of cleanup;
- Measure mass and volume of excavated material or groundwater;
- Measure contaminant levels of excavated material or groundwater;
- Health and safety monitoring; and
- Measure environmental compliance (losses to the environment).

The locations where project monitoring may occur are:

- excavation site;
- treatment site;
- disposal site;
- subsurface (groundwater, vadose zone, in-situ treatment access points); and
- ex-situ groundwater treatment site.

Table 7.1 summarizes the purposes of project monitoring, typical sample points and types of monitoring methods and equipment at each discrete location at a site.

7.2 Post-Project or Long-term Monitoring

Post-project monitoring is that monitoring which is conducted after the remedial activities are completed. On-going activity such as the operating of groundwater treatment plants, the maintenance of equipment and the maintenance of security may be continuing but the remedial phase is completed. The purpose of post-project monitoring is:

- Determine compliance with cleanup objectives;
- Determine residual risk or toxicity;
- Measure reductions in environmental exposure or improvements in biological population;
- Satisfy regulatory requirements;
- Monitor storage or disposal sites;
- Measure damage caused by project activities; and
- Fill information gaps.

The locations where post-project monitoring is needed are essentially the same as for project monitoring:

- excavation site;
- excavated material treatment site;
- disposal site;
- subsurface (groundwater, vadose zone, in-situ treatment access points); and
- ex-situ groundwater treatment site.

Table 7.2 summarizes the purposes of post-project monitoring, typical sample points and types of monitoring methods and equipment at each discrete location at a site.

Project Monitoring Location	Purposes of Monitoring	Typical Sample Points	Types of Sampling
Excavation site	<ul style="list-style-type: none"> • Confirm extent of subsurface contamination • Volume of excavated material • Compliance with contractual obligations 	<ul style="list-style-type: none"> • Walls and floor of excavation • Excavated material at point of removal or at transfer point • Air monitoring at arbitrary site boundary • Water samples from runoff, leachate or supernatants 	<ul style="list-style-type: none"> • Grab samples -solids and water • Water well samples (bailers, pumps) • Core samples • Various air sampling devices • Spatial and temporal composites • Transits and levels to determine final grades
Excavated material treatment site	<ul style="list-style-type: none"> • Determine fate of contaminants (mass balance) • Monitor process parameters • Regulatory compliance 	<ul style="list-style-type: none"> • Feed material (batch or continuous) • Treated material (batch or continuous) • Process intermediate points • Off-gases • Other effluents and by-products • Inside of reactors and pipes before and after project 	<ul style="list-style-type: none"> • Grab samples • Composites • Gas sampling using trap samplers • Volume or mass measurement of feed and treated material
Disposal site	<ul style="list-style-type: none"> • Verify mass or volume of disposed material • Verify contaminant levels • Monitor air emissions • Measure pre-disposal groundwater conditions • Verify final grades and contours 	<ul style="list-style-type: none"> • Entrance to disposal site • Air quality at boundaries of site • Groundwater around site 	<ul style="list-style-type: none"> • Weigh scales or volume measuring system (lugger boxes) • Grab samples • Monitoring wells -bailers and pumps • Various air samplers • Transits and levels
Subsurface	<ul style="list-style-type: none"> • Monitor performance of in-situ treatment or extraction wells • Track movement of plume or free product • Monitor drinking water in nearby wells 	<ul style="list-style-type: none"> • Vadose zone air and soil • Groundwater (possibly more than one aquifer) • Tap water from nearby residences • Free product (LNAPL or DNAPL) • Off-gases from vent wells 	<ul style="list-style-type: none"> • Grab and core samples (soil and sediment) • Vadose zone air samplers • Monitoring wells - bailers and pumps • Grab samples of groundwater discharge points (springs, surface water) • Various air samplers
Ex-situ groundwater treatment site	<ul style="list-style-type: none"> • Determine fate of contaminants (mass balance) • Monitor process parameters • Regulatory compliance 	<ul style="list-style-type: none"> • Feed groundwater • Treated groundwater • Process intermediate points • Off-gases • Other effluents and by-products • Inside of reactors and pipes before and after project 	<ul style="list-style-type: none"> • Grab samples • Composites • Gas sampling using trap samplers • Volume measurement of feed and treated groundwater

Table 7.1 Purpose, location and types of project monitoring (monitoring done during remediation phase).

Project Monitoring Location	Purposes of Monitoring	Typical Sample Points	Types of Sampling
Excavation site	<ul style="list-style-type: none"> • Verify final grading and re-vegetation • Monitor biological indicators 	<ul style="list-style-type: none"> • Usually visual observation only • Possibly sample biota 	<ul style="list-style-type: none"> • Transits and levels • Biological monitoring/sampling over long-term
Excavated material treatment site	<ul style="list-style-type: none"> • Verify decommissioning of treatment technology 	<ul style="list-style-type: none"> • Visual observation • Soil samples (soil at treatment site) 	<ul style="list-style-type: none"> • Grab samples; usually a one-time event
Disposal site	<ul style="list-style-type: none"> • Determine leakage of disposal site if any • Monitor leachate collection/treatment facilities • Observe final grades and revegetation • Check for volatile gas emissions • Monitor integrity of cap and fill 	<ul style="list-style-type: none"> • Groundwater upgradient and downgradient of site • Collected leachate storage tanks or lines • Landfill gas vents • Landfill cover 	<ul style="list-style-type: none"> • Groundwater monitoring wells • Grab samples of collected or treated leachate • Various air sampling devices • Cores of cover and fill
Subsurface	<ul style="list-style-type: none"> • Monitor remaining plume movement and trends in contaminant levels • Monitor drinking water in nearby wells • Monitor off-gases from vent wells 	<ul style="list-style-type: none"> • Groundwater upgradient, in, and downgradient of plume • Tap water from nearby residences • Vent wells 	<ul style="list-style-type: none"> • Grab and core samples (soil and sediment) • Vadose zone air samplers • Monitoring wells - bailers and pumps • Grab samples of groundwater discharge points (springs, surface water) • Various air samplers
Ex-situ groundwater treatment site	<ul style="list-style-type: none"> • Determine fate of contaminants (mass balance) • Monitor process parameters • Regulatory compliance • Monitor decline in contaminant levels in pumped groundwater (to make decision to cease operations) 	<ul style="list-style-type: none"> • Feed groundwater • Treated groundwater • Process intermediate points • Off-gases • Other effluents and by-products • Inside of reactors and pipes before and after project 	<ul style="list-style-type: none"> • Grab samples • Composites • Gas sampling using trap samplers • Volume measurement of feed and treated groundwater

Table 7.2 Purpose, location and types of post-project or long-term monitoring.

7.3 Summary

The goal of this chapter was to provide a very brief introduction to monitoring. The principles described were intended to provide basic knowledge for a project manager tasked to develop a monitoring plan, assess monitoring work and/or hire monitoring sub-contractors.

The important elements of a monitoring plan are:

- plan the monitoring in advance;
- use appropriate expertise;
- use a mass balance approach if possible;
- use independent parties for monitoring or engage an auditor;
- specify sampling and laboratory methods in advance; and
- develop a Quality Assurance/Quality Control (QA/QC) protocol

It is important to separate the monitoring into two distinct components: project monitoring and post-project or long-term monitoring.

SITE REMEDIATION TECHNOLOGIES A REFERENCE MANUAL

REFERENCES

American Petroleum Institute (API). 1989. **A Guide to the Assessment and Remediation of Underground Petroleum Releases.** API Publication 1628.

American Petroleum Institute (API). 1995. **Petroleum Contaminated Low Permeability Soil: Hydrocarbon Distribution Processes, Exposure Pathways and In-situ Remediation Technologies.** Health and Environmental Sciences Department Publication Number 4631, September, 1995.

Canadian Council of Ministers of the Environment, 1991. **Interim Canadian Environmental Quality Criteria for Contaminated Sites.** Report CCME EPC-CS34, Sept. 1991.

CPPI - Canadian Petroleum Products Institute. 1994. **Manual for Remediation of Groundwater Containing Dissolved and Free Phase Hydrocarbons.** CPPI Report No. 94-1. 60p.

Chemical Waste Management. 1993. **X*TRAX Low Temperature Thermal Desorption Treatability Study on Thunder Bay Harbour Sediment.** Report submitted to the Great Lakes Cleanup Fund in fulfilment of contract.

Cognis Inc. 1993. **Cognis TerraMet Metal Extraction Phase I and II Treatability Studies, St. Mary's River Sediment.** Report submitted to the Great Lakes Cleanup Fund in fulfilment of contract.

Energy and Environmental Research Corp., 1993. **Technology Evaluation Report: Eco Logic International Gas-Phase Chemical Reduction Process, Bay City, Michigan.** SITE Program Demonstration Report, USEPA Contract No. 68-C9-0033, Oct. 1993.

Hansen, S.P., R. Gumerman, and R. Culp. 1979. **Estimating Water Treatment Costs. Volume 3: Cost Curves Applicable to 2500 gpd to 1 mgd Treatment Plants.** EPA-600/2-79-162c. USEPA, Municipal Environmental Research Laboratory, Cincinnati, OH.

Hinchee, R.E. 1994. **Air Sparging for Site Remediation.** Lewis Publishers, Chelsea, Michigan.

Jackman, A.P., and R.L. Powell. 1991. **Hazardous Waste Treatment Technologies: Biological Treatment, Wet Air Oxidation, Chemical Fixation, Chemical Oxidation.** Noyes Publications. p. 62.

Keely, J.F. 1989. **Performance Evaluations of Pump-and-Treat Remediations,** EPA Superfund Ground Water Issue, EPA/540/4-89/005.

- Liptak, B., editor. 1974. **Environmental Engineers' Handbook Volume I: Water Pollution**. Chilton Book Co., Radnor, Pa., USA.
- Noonan, D.C. and J.T. Curtis. 1990. **Groundwater Remediation and Petroleum. A Guide for Underground Storage Tanks**. Lewis Publishers, Chelsea, Michigan.
- Ontario Ministry of the Environment. 1992. **Guidelines for the Protection and Management of Aquatic Sediment Quality in Ontario**. Ontario Report ISBN 0-7729-9248-7, June 1992.
- Ontario Ministry of the Environment. 1992. **Fill Quality Guidelines for Lakefilling in Ontario**. Ontario Report ISBN 0-7729-9329-7, June 1992.
- Paterson, J.W. 1978. **Wastewater Treatment Technology**. Ann Arbor Science, Ann Arbor, Mich., USA.
- Resources Conservation Co., 1994. **B.E.S.T. Bench Scale Treatability Final Report, Thunder Bay Harbour Site**. Report submitted to the Canada's Great Lakes Cleanup Fund in fulfilment of contract.
- Russell, H., Matthews, J. and Sewell, G. 1992. **TCE Removal from Contaminated Soil and Ground Water**. Ground Water Issue. January 1992. EPA/540/S-92/002. 10p.
- Stokman, G.N., and W.A. Bruggeman. 1993 **Remediation of Contaminated Sediment: Developments in the Netherlands**. Proceedings CATS II Congress, Antwerp, Belgium, November 15-17, 1993.
- USEPA. 1987. **Air Stripping of Contaminated Sources - Air Emissions and Controls**. EPA Report 450/3-87-017.
- USEPA. 1990a. **Handbook of In Situ Treatment of Hazardous Waste-Contaminated Soils**. EPA/540/2-90/002. 157p.
- USEPA. 1990b. **Soil Washing Treatment**. EPA Report 540-2-90-017.
- USEPA. 1990c. **The Superfund Innovative Technology Evaluation Program: Applications Analyses**. EPA/540/A5-89/012.
- USEPA. 1991. **Soil Vapour Extraction Technology Reference Handbook**. EPA/540/2-91/003. p. 90.
- USEPA Technology Innovation Office. 1992. **Innovative Treatment Technologies: Semi-Annual Status Report**. EPA/542/R-92/011, October 1992.
- USEPA. 1993a. **Remediation Technologies Screening Matrix and Reference Guide, Version 1**. Report EPA 542-B-93-005, July 1993. 142p.
- USEPA. 1993b. **In Situ Treatment of Contaminated Ground Water: An Inventory of Research and Field Demonstrations and Strategies for Improving Ground Water Remediation**. EPA/500/K-93/001, January 1993. 17p.

USEPA, 1994. **Assessment and Remediation of Contaminated Sediments (ARCS) Program Remediation Guidance Document**. EPA Report 905-B94-003.

Wagner, K., K. Boyer, R. Claff, M. Evans, S. Henry, V. Hodge, S. Mahmud, D. Sarno, E. Scopino and P. Spooner. 1986. **Remedial Action Technology for Waste Disposal Sites**. Noyes Data Corporation, Park Ridge, NJ.

Wardlaw, C., W. Randle and D. Brendon, 1995. **Results of Canada's Contaminated Sediment Treatment Technology Program for the Great Lakes**. Proceedings of Sediment Remediation '95, Windsor, Ontario, Canada, May 8-10, 1995.

Toronto Harbour Commissioners, 1993. **Report on the Treatment of the Toronto Harbour Sediments at the THC Soil Recycling Plant**. Report submitted to the Canada's Great Lakes Cleanup Fund in fulfilment of contract.

Wastewater Technology Centre. 1992. **Iron and Manganese Removal from Groundwater: Enhanced Aeration Processes**. Groundwater and Soil Remediation Program (GaSReP) Unpublished Report No. 89-91-07, Environment Canada, Burlington, Ont., Canada.

Water Technology International Corp. 1996a. **REMTEC Database**. Electronic database marketed by WTI Corp., Burlington, Ontario, Canada.

Weston, Roy. 1988. **Remedial Technologies for Leaking Underground Storage Tanks**. Lewis Publishers. 216p.

Weston, R.F. and University of Massachusetts. 1990. **Remedial Technologies for Underground Storage Tanks**. Lewis Publishers, Chelsea, Michigan. pp. 216.

SUGGESTED READING

Canter, L.W. and R.C. Knox. 1985. **Ground Water Pollution Control**. Lewis Publishers Inc., Chelsea, Mich., USA.

Freeze, R.A. and J.A. Cherry. 1979. **Groundwater**. Prentice-Hall Inc., Englewood, Calif., USA.

National Research Council (US). 1994. **Alternatives for Groundwater Cleanup**. National Academy Press, Washington, DC.

USEPA. 1990a. **Handbook of In Situ Treatment of Hazardous Waste-Contaminated Soils**. EPA/540/2-90/002. 157p.

USEPA. 1994. **Assessment and Remediation of Contaminated Sediments (ARCS) Program Remediation Guidance Document**. EPA Report 905-R94-003. Oct. 1994.

Wagner, K., K. Boyer, R. Claff, M. Evans, S. Henry, V. Hodge, S. Mahmud, D. Sarno, E. Scopino and P. Spooner. 1986. **Remedial Action Technology for Waste Disposal Sites**. Noyes Data Corporation, Park Ridge, NJ.

Appendix A

Glossary of Terms and Acronyms

GLOSSARY OF TERMS

(for list of Acronyms see last page of Glossary)

Acclimated - in biological treatment refers to micro-organisms which have been given time to grow and reproduce in soil, sediment, water or laboratory media similar to or the same as the media which is to be treated. The purpose of acclimation is to reduce the “shock” to the micro-organisms when they are added to the media for the purposes of remediation.

Aliphatic - organic compounds which are made up of straight or branched chains (but no ring structures); includes alkanes, alkenes and alkynes.

Aromatic - organic compounds which contain cyclic or ring structures; the most simple of these is benzene (thus a six carbon ring is often called a “benzene ring”).

Amendment - in biological treatment of soil or sediment refers to an additive which is designed to add bulk to the media and by adding bulk allows a fuller and more even distribution of air and water. In some cases the amendment is also selected to add an additional carbon source and growth site for the micro-organisms. Typical amendments are wood chips, straw and peat moss.

Advection - the movement of property (heat) or substance (chemical) through the physical movement of a carrier fluid (air or water). Advection is often the dominant mechanism of movement over other mechanisms such as diffusion (of chemical) or radiation (of heat).

Aquifer - a subsurface zone from which water can be pumped on a continuous or semi-continuous basis. Typically these zones have higher than average hydraulic conductivities. Typically aquifers which are used for water supply are comprised of unconsolidated sands and gravels, permeable sedimentary rock and heavily fractured rock (Freeze and Cherry, 1979). One aquifer may be separated from another aquifer by an horizontal “aquitard” or by a vertical barrier.

Aquitard - a layer of material which is either impermeable to water or is less permeable than another layer and therefore separates one aquifer from another. Aquitards are usually thought of as lying horizontally although they may have severe slopes and undulations to them.

Bedrock - the layer of rock of any origin beneath or at the ground surface which is continuous and essentially immovable. Fractures in this rock provide space for the storage and movement of groundwater. The water table may be above or below the bedrock surface.

Benthic - refers to organisms, samples or bottom strata related to, living in or associated with the sediment layer at the bottom of a lake, ocean or river.

Bioaugmentation - the adding of micro-organisms to a biological treatment system. The added organisms may be naturally occurring ones which have been cultured for this use or they may be genetically engineered micro-organisms (GEMs).

Biodegradation - the process of destruction or mineralization of either natural or synthetic materials by the micro-organisms of soils, waters or wastewater treatment systems.

Biostimulation - any attempt to stimulate the growth of microbial populations in a biological treatment system is referred to as biostimulation. The most common form of biostimulation is the adding of nutrients, mainly nitrogen, phosphorous and potassium. Other possible additives are carbon sources such as glucose, micronutrients, proteins, enzymes and hormones.

Borehole - a hole drilled or bored into the earth, and into which casing or screen can be installed to construct a well.

Chelating Agent - a chemical compound with a central metal ion and two or more organic complexes with the property of attracting and attaching to metal ions. Chelating agents are used in analytical laboratories and in metal treatment technologies.

Composite Sample - a sample obtained by mixing several discrete samples or representative portions thereof into one bottle. The discrete samples may have been collected from different locations of a site and thus be a spatial composite or may have been collected from the same location over time and thus be a temporal composite.

Control - in experimental work or treatability studies the hypothesis is often (should always be) tested by comparing the effectiveness of the proposed method against the effectiveness of either existing methods or no method at all. The tests which the proposed method are compared to are called controls. Control samples are commonly used in biological treatability tests on soil. One control is the soil with no additives or energy inputs. Another control might be with energy (mixing) but no other additives. Another control might have air (oxygen) added but no other additives. Any number of control samples may be needed to thoroughly test the hypothesis.

Dispersion - the spreading of a substance into a system (soil, water or air) by any mechanism of transport.

DNAPL - Dense-Non-Aqueous-Phase Liquids. Organic liquids that are more dense than water. They often coalesce in an immiscible layer at the bottom of a saturated geologic unit.

Elutriate - 1. the process of washing a solid and then separating the wash solution from the cleaned solids. 2. the wash solution from an elutriation process after separation from the solids.

Free Product - a liquid contaminant which is present in the subsurface in sufficient quantity to fill the pore spaces of the soil or bedrock is termed a free product. This liquid behaves somewhat like groundwater in that it moves through the pore spaces and if present in very large quantity can be pumped to the surface. Free products may be lighter than water, denser than water, soluble in water, non-soluble in water, more viscous (flows more slowly) than water or less viscous (flows faster) than water.

GEMS - Genetically Engineered Micro-Organisms. In site remediation work this refers to organisms which have had genetic material added, deleted or altered to make them more efficient at degradation of certain chemical compounds.

Groundwater - 1. all water below ground surface 2. the water in the saturated zone (i.e. below the water table). Water under hydrostatic pressure in interconnected pores of the saturated zone emerges from springs and enters wells.

Heterogeneity - refers to the geologic conditions at a site. Soil, sediment or bedrock that is heterogeneous is made up of two or more layers and/or two or more types of material mixed together. Heterogeneous material can be more difficult to cleanup using in-situ techniques or pump and treat systems because the groundwater takes preferential flow paths through the more permeable material.

Homogeneity - refers to the geologic conditions at a site. Soil, sediment or bedrock that is made up of one layer of uniform material is said to be homogeneous. If the layer is made up of sand, gravel or uniformly fractured rock then in-situ treatment and pumping systems have a higher likelihood of success. If the layer is made up of clay or poorly fractured rock then in-situ treatment and pumping may be difficult.

Hydraulic Conductivity - a measure of the permeability of soil or rock to the passage or flow of a given fluid. Hydraulic conductivity is a constant for a certain soil or rock and is measured either in the laboratory or using pumping tests in the field. Darcy's Law of groundwater flow is:

$$\text{Flow velocity (m/s)} = \text{Hydraulic conductivity (m/s)} \times [\text{height difference of fluid (m)}/\text{distance(m)}]$$

Leachate - in the site remediation field, leachate is a solution produced by the percolation of water through solid waste, contaminated soil or other solid media. As water passes through the solid media chemical constituents or small particles associated with the solid may become suspended or dissolved in the water. Leachate can also be produced in the laboratory by passing water at set pH and temperature through a test sample of the solid media.

LNAPL - Light-Non-Aqueous-Phase-Liquids. Fluids that are less dense than water. They are capable of forming an immiscible layer that floats on the water table. (e.g., petroleum hydrocarbons).

Macrophytes - literally this means "large plants". For the purposes of site remediation the term is used to differentiate "large plants" from single cell or microscopic plants. Typically macrophytes have roots, stems and green leaves although in some cases the larger fungi would also be considered macrophytes.

Non-Aqueous Phase Liquids (NAPLs) - liquid chemicals or mixtures which dissolve poorly or not at all in water (and hence can be found as a free liquid in the subsurface). NAPLs can be Light (LNAPL) or Dense (DNAPL) in relation to water.

Permeability - the ease with which a fluid flows through the pores and cracks of a soil or rock. Note that permeability is different than porosity. A porous soil or rock is usually but not always more permeable than a less porous rock. The permeability depends on whether the soil or rock has channels connecting the pores and cracks. Permeability is very similar to hydraulic conductivity and has the same units (m/s) but the permeability of a soil or rock is independent of the fluid flowing through it whereas hydraulic conductivity does depend on the fluid.

Plume - the region of groundwater contaminated by chemical pollutants. Usually a plume is groundwater with **dissolved** contaminants in it but in some cases the contaminants may be suspended in the groundwater or the plume may be made up largely of free product flowing through the soil or rock.

Porosity (of soil or rock) - the amount of space within the soil or rock which is not solid matter. Pore spaces may be filled by water, air or other liquids or gases. Porosity is measured by determining the volume of water held in a sample of soil or rock of known total volume. Porosity is expressed as a percentage of the total volume of material.

Remediation - the improvement of a contaminated site to prevent, minimize or mitigate damage to human health or the environment. Remediation involves the development and application of a planned approach that removes, destroys, contains, or otherwise reduces availability of contaminants to receptors of concern.

Saturated Zone - 1. the zone below ground surface where no air or gas exists as a separate phase and therefore all pore spaces are filled with water (air or gas may exist in a dissolved phase or as bubbles). 2. the zone where voids in the soil or rock are filled with water at greater than atmospheric pressure. In an unconfined aquifer, the water table forms the upper boundary of the saturated zone.

Sediment - an assemblage of individual particles of various origin either suspended in a water column (suspended sediment) or situated at the bottom of a surface water column (benthic sediment). Sediment particles originate by the weathering of rocks and the erosion of soil and are transported to a water column by air, water or ice, and also originate by other processes such as chemical precipitation from solution, biological growth (and death), or secretion by organisms. Sediment is identical to soil except that it exists in the aquatic environment.

Semi-volatile (chemical) - substances which easily form a vapour at temperatures between about 110° C and 250° C. Note that semi-volatiles will form vapors at lower temperatures but not in significant quantities.

Soil - an assemblage of individual particles of various origin situated above the bedrock. Particle sizes range from very fine clays (< 0.001 mm) through silts and sands, to gravels (>2.0 mm). Geologists refer to soil as "sediment". May be saturated or unsaturated. Soil contains pore spaces which allow for storage and movement of pore water, groundwater, air or other vapour.

Soil Gas - the vapour or gas that is found in the pore spaces in the unsaturated zone.

Smearing - smearing occurs when a free product exists at the surface of the water table (ie. the free product is an LNAPL) and the water table level fluctuates. The fluctuations in the water table cause the free product to also rise and fall and this “smears” the product on the soil or rock particles. A good analogy is oil floating on water in a pail. If some of the water is removed the water level drops and an oil film is left on the sides of the pail down to the new water level. Smearred product is more difficult to cleanup than free product.

Unconfined Aquifer - an aquifer that is not bounded by an overlying layer of distinctly lower permeability (ie. the upper layer or water table is at atmospheric pressure).

Vadose or Unsaturated Zone - the zone below ground surface (and normally above the saturated zone) where air, water and solid phases exist together. Usually the zone closest to the ground surface.

Volatile (Chemical) - substances (usually organic substances) which easily form a vapour at ambient temperature (and up to 110° C) and ambient pressure are said to be volatile. In scientific terms these substances have a low vapour pressure.

Volatile Organics/Volatile Organic Compounds (VOC) - liquid or solid organic compounds that tend to pass into the vapour state at atmospheric pressure and ambient temperature.

Water Table - in a simple hydrogeologic situation the water table is the surface of the groundwater. In some cases groundwater is confined below an aquitard and is under pressure. When a well is drilled into this formation water may flow upward under pressure and the well is called “Artesian”. In these cases the water table is the height to which the water would rise if it were not confined. In other cases water is perched on top of an aquitard. If the aquitard were not present the water would sink until it reached the point of zero pressure difference. In this case the water table can be defined as the surface of the water or as the level to which the water would sink if it could, depending on the nature of the project at hand.

ACRONYMS

BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CCME	Canadian Council of Ministers of the Environment
CDF	Confined Disposal Facility (facility for the disposal of dredged sediment)
DCE	Dichloroethylene
DESRT	Development and Demonstration of Site Remediation Technologies
DNAPL	Dense Non- Aqueous Phase Liquid
GEMS	Genetically Engineered Micro-organisms
LNAPL	Light Non-Aqueous Phase Liquid
NCSRP	National Contaminated Sites Remediation Program (Canada)
O&G	Oil and grease
PAH	Polynuclear Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyls
PCP	Pentochlorophenol
SITE Program	Superfund Innovative Technology Evaluation Program (US EPA)
Superfund	A program to remediate seriously contaminated sites in the US.
SVE	Soil Vapour (Vacuum) Extraction
SVOC	Semi-Volatile Organic Compound
TCE	Trichloroethylene
TPH	Total Petroleum Hydrocarbons
VOC	Volatile Organic Compound
VC	Vinyl Chloride

Appendix B

Case Studies

Five (5) workshops on the management of federal contaminated sites were delivered to federal employees, between October and December of 1996. The workshops were sponsored by the federal interdepartmental Contaminated Sites Management Working Group (CSMWG). This appendix contains summaries of the case studies presented during the 'Site Remediation Technologies' session of the workshops. The CSMWG would like to thank those who provided case studies and shared their experiences and 'lessons learned' with the audience.

Pumping and Treatment of Groundwater at the Gloucester Landfill Site

Ralph Ludwig
Water Technology International
Burlington, Ontario

The Gloucester Landfill site is located south of Ottawa in Ontario, Canada. The site served as a municipal waste dump from approximately 1957 to 1980. Between the years 1969 and 1980, the site also served as a disposal site for federal laboratory, university and hospital wastes. These wastes were disposed of in what was called the Special Waste Compound. Wastes disposed of in the Special Waste Compound consisted primarily of organic solvents although other compounds including DDT, arsenic, cyanide, copper sulphate, hydrofluoric acid, metal carbonates and wood preservative solutions were also reportedly disposed of at the site. Disposal practices within the Special Waste Compound involved the excavation of trenches to depths of four metres or more followed by the placement and subsequent detonation of the wastes in the trenches. Records pertaining to the volumes of waste materials disposed of in the Special Waste Compound as well as the frequency of disposal events within the compound were not kept.

The site is situated on top of a complex sequence of glaciofluvial and littoral deposits of Quaternary age. Two aquifers occur beneath the site; a shallow unconfined aquifer and a deep confined aquifer. The shallow aquifer averages approximately 6 metres in thickness while the deep aquifer averages more than 20 metres in thickness. Both aquifers have been extensively impacted by contaminants released at the site.

The confined aquifer has been significantly impacted by wastes disposed of in the Special Waste Compound. Contaminants which have been detected in the confined aquifer have included 1,4-dioxane, tetrahydrofuran, diethyl ether, trichloroethylene (TCE), 1,1-dichloroethane, benzene, 1,1-dichloroethylene, tetrachloroethylene, and 1,1,2-trichlorotrifluoroethane. The most mobile contaminants at the site are 1,4-dioxane, tetrahydrofuran and diethyl ether. 1,4-dioxane is of greatest concern due to its identification by the USEPA as a probable human carcinogen.

A 29-well pump and treat system is currently being operated by WTI at the site to contain the contaminant plumes and to remove contaminant mass from the aquifers. The system pumps and treats approximately 500 l/min from the deep aquifer and 250 l/min from the shallow unconfined aquifer and has been in operation since 1992. The extracted groundwater is treated at the site using a UV-hydrogen peroxide oxidation process. The treatment involves first adding acid to the influent groundwater to bring down the pH; then passing the groundwater through a series of UV lamps in the presence of hydrogen peroxide to destroy contaminants of concern; followed by addition of caustic (NaOH) to again bring up the pH. After addition of caustic, the treated groundwater is reinjected at one or more of five locations upgradient of the site.

The pump and treat system has been successful in containing contamination at the site and contaminant mass is gradually being removed from the aquifers. The time frame over which the pump and treat system will need to be operated in order to achieve clean up objectives is not yet known. Groundwater monitoring carried out on a regular basis at the site is being used

to verify containment of the contaminant plumes and will be used to provide insight into the progress of clean up at the site.

Some 1,4-dioxane contamination exists beyond the influence of the deep aquifer pumping system. A human health risk assessment conducted by WTI has indicated that the 1,4-dioxane contamination (outside the influence of the pump and treat system) does not pose a risk to human health. The 1,4-dioxane contaminant concentrations beyond the limits of the pump and treat system are expected to steadily decrease due to the natural attenuation processes of dispersion and dilution.

CFB Borden In-situ Treatment Pilot Project

Presented by
Jim Barker
University of Waterloo
Waterloo, Ontario

Precis*

The University of Waterloo has been conducting field research, development and demonstration of plume control and in-situ treatment methods at CFB Borden, Ontario, for a number of years. The CFB Borden test site has many features which make it ideal for studying the movement of groundwater and the fate of contaminants in the subsurface environment.

Several technologies have been or are being developed by the University of Waterloo with field study at CFB Borden. These generally fall under one of two types of in-situ strategies: intrinsic remediation and semi-passive in-situ remediation. Intrinsic remediation is a type of remediation where little or no intervention in the subsurface is required. Intrinsic remediation requires a high level of monitoring to determine the mechanisms of natural attenuation of contaminants and the fate of contaminants. It is, of course, only suitable for sites where natural attenuation results in the lowering of contaminant levels within the property boundaries or the approved attenuation zone. Semi-passive in-situ remediation techniques involve relatively minor disturbances to the subsurface environment. Semi-passive techniques being developed and/or studied at the CFB Borden test area are:

- Funnel-and-Gate™ containment/treatment system
- biosparge fence
- alcohol and water flushing
- oxidant flushing
- treatment walls
- soil venting and bioventing.

The Funnel-and-Gate™ concept, developed by the University of Waterloo, involves the placement of a physical barrier to groundwater flow with a small opening or gate in the barrier. The barrier causes groundwater to flow towards and through the gate. Some form of treatment is then installed at the gate so that the groundwater is treated as it flows through the gate. The barrier may be a slurry trench, vibrated beam wall, plastic trench liner, jet grout wall auger mix bentonite wall, sheet pile wall or the “Waterloo Barrier”. The table summarizes the types of treatment which can be installed at the gate.

* This precis by Craig Wardlaw, Water Technology International.

Most of the techniques being tested at the Borden site will be commercially available in the next few years.

Gate Treatment Technique	Contaminants Treated	Status
Metal precipitation	Most metals	Field testing underway
Phosphate removal by precipitation	Phosphate	Laboratory testing
Enhanced organic sorption	Hydrophobic organics	Field testing underway
Dentrification	Nitrate	Field testing commencing
Air sparging	Volatile and semi-volatile organics	Laboratory
Enhanced aerobic biodegradation - air sparging	Oxidizable organics	Pilot testing commencing
Enhanced aerobic biodegradation - oxygen releasing solids	Oxidizable organics	Pilot testing commencing
Iron catalyzed reductive dechlorination	Chlorinated organics	Commercially available

Types of gate treatments for the Waterloo Funnel-and-Gate™ system.

Bioremediation of Heavy Hydrocarbon Contaminated Soils Preliminary Report - CFB Trenton FFTA Project

**J.G. Critchley
Department of National Defence (Canada)
Ottawa, Ont., K1A**

PRECIS*

The Department of National Defence (DND) has been seeking soil remediation options other than low temperature thermal desorption (LTTD) for heavy hydrocarbons, typical of those found in fire fighter training areas. Although effective, LTTD has been costing \$40 to \$70 per tonne of soil and has been requiring a high degree of contract supervision. The result is that, overall, LTTD is an expensive option. DND decided to evaluate several bioremediation options which have the potential to cost less than LTTD.

Recent papers from bioremediation symposia have been heralding the advantages of white rot fungus for the remediation of soils contaminated with recalcitrant organics, including heavy hydrocarbons. However there have been few successful field-scale projects which have demonstrated the white rot fungus "technology". In addition, various other proprietary bioremediation technologies have been developed but have not been able to demonstrate their effectiveness in controlled field-scale experiments.

As a result, DND decided to conduct a demonstration project to compare and evaluate some of the different bioremediation technologies. Environment Canada and Transport Canada supported the project financially and several vendors provided services at no charge.

The demonstration project was conducted at CFB Trenton from July 1995 to November 1995. Ten technologies, including controls, were evaluated. A treatment pad of approximately 2500 m² was constructed at CFB Trenton, Ontario. Soil contaminated with hydrocarbons was excavated from the fire-fighter training area at CFB Trenton and placed on the pad. Ten different techniques were to be compared and the soil on the pad was divided such that approximately 100 tonnes was allocated to each of the ten cells and for the control piles. The entire project was supervised by one project manager. The treatment period was eight weeks. There was no fixed remediation objective but results were to be compared with any applicable provincial soil remediation criteria for Total Petroleum Hydrocarbons (TPH) and Mineral Oil and Grease (MOG).

The ten technologies and controls were:

- White Rot Fungus mixed with compost, with turning;
- Generic treatment with compost and poultry manure, with turning;
- Generic treatment with compost and commercial fertilizer, with turning;
- Generic treatment with compost and commercial fertilizer, without turning;

* This precis by Craig Wardlaw, Water Technology International.

- Generic treatment with commercial fertilizer, without turning;

- The Bioquest process adapted to ex-situ treatment (uses an inoculum);
- Bioquest control, using oxygenated water but no inoculum;
- The Hobbs & Miller process;
- The Grace Dearborn Daramend process; and
- Biotic control (no additives) with turning.

Although all soil was mixed prior to subdividing into the ten 100 tonne parcels, there was some variability in the initial levels of TPH and MOG in the plots. All plots reached an asymptotic level in 4 weeks. All treatments reached levels of TPH and/or MOG which would meet most provincial criteria. Therefore any of these techniques could be used for remediation of soils from firefighter training areas. The selection of a technology will be site specific and will depend on criteria such as cost, land area available, locale, etc.

The results presented here are preliminary. A generic guide to bioremediation of firefighter training area soils will be produced and the complete results of this project will be published.

**Remediation of the Former Firefighter Training Site
at the Sept-Iles Airport.**

**Loraine Pichette Ing.
Environment Agent
Professional and Technical Services
Airport Groups
Transport Canada
Tel: (514) 633-3824 Fax: (514) 633-3250**

Summary:

The former firefighter training site of Sept-Iles is located on a high, sandy terrace, along the St-Lawrence River. Over the years, firefighter training had caused hydrocarbon contamination of the sub-surface soils. A measurable amount was also detected in the groundwater about 30 metres in depth. This aquifer is used by the inhabitants of the beaches as a drinking water source. A further risk study has shown a possible migration of contaminating material. It was then decided to remediate the soil at the former firefighter training grounds.

In view of the particular soil contamination configuration, an in-situ solution was considered and later tested in a full-scale in-situ pilot trial. Study results have shown that the best cost/efficiency compromise could be found in the combination of two treatment technologies: (i) an in-situ bio-venting for the section affected at depth, and (ii) soil excavation and bio-degradation in piles for the surface contamination.

As a follow-up, groundwater quality measurements are regularly taken at the firefighter training site as well as in the residential area surrounding the site. Remediation works are presently in progress, and final results will be known in two years' time. The pre-treatment studies, however, offer us great hope for the success of the operation.

Pumping and Treatment of Groundwater in Rigaud, PQ

**Alain Chartrand
Operator, Revenue Canada College, Rigaud
PWGSC
Tel: (514) 496-6847 Fax: (514) 283-6847
October 31, 1996**

Summary:

In the course of a test conducted by the City of Rigaud, traces of oil were found in the waste water of the municipality.

The firm in charge of the study discovered that the contaminating material originated upstream, from the drainage waters of a Revenue Canada College.

We proceeded immediately to investigate and discovered a small leak coming from pipes located between the underground tanks, near the building.

Emergency repairs were then initiated and remediation of soils and water was started.

PWGSC called in the expertise that was necessary for a successful operation that met the norms and followed the environmental regulations applicable to this type of project. The ultimate aim was an efficient process that respected the environment while keeping a realistic view of the implied costs.

**Cleaning of Contaminated Soils at Ste-Anne-des-Plaines
Experience and Post-Mortem: Global View**

**Sylvain Bouchard
Regional Technical and Mechanics Agent
Correctional Services Canada
Tel: 664-6602, Fax: 664-6600
October 31, 1996**

Summary:

In June 1994, Correctional Service of Canada (CSC) started a project for the replacement of seven underground petroleum product storage tanks at the Ste-Anne-des-Plaines penitentiary. Since the beginning of excavation, the intervening parties noticed a major problem of soil contamination from heavy hydrocarbons (heavy oil #6).

Faced with the different options: either characterising the area before proceeding with work, or soil excavation and temporary storage. Considering the urgent need for tank replacement and due to tender process delays, CSC chose the latter option. Soils were temporarily placed in airtight containers and stored in-situ. Each of the containers contained about 18 metric tonnes of material. All the necessary chemical analyses for soil treatment having been completed, it appeared that out of 104 containers with contaminated soil, 91 had a contamination level higher than the MEFQ C criteria for mineral oils and grease (5,000 ppm). Forty-five (45) containers were filled with broken stones intermixed with clay, while 46 carried broken stones.

CSC, Environment Canada representatives, and the designated consultant (Dessau Environment) have collaborated closely in the research and evaluation of the different potential treatment scenarios. Alternatives such as bio-remediation, incineration, recycling, washing and pyrolysis were examined. In the absence of other ideas, in-situ encapsulation and ex-situ containment were considered. For technical as well as economical and administrative reasons, only two options were possible: ex-situ containment in a maximum security cell and/or a soil washing treatment.

Contaminated soils containing broken stones mixed with clay (45 containers) were not suitable for treatment and had to be disposed of ex-situ (landfill). For the soils from the other 46 containers, composed almost exclusively of broken stones with an average oil and grease concentration of 21,481 ppm, the washing process would allow CSC to reach the objective of 1,000 ppm (MEFQ B criteria) in under eight weeks. This simple and ingenious process consisted of a series of sieves and conveyors which were used to separate and bring the material being treated to a mobile washing unit which used using hot water and bio-degradable soap. At the end of the treatment train, water and oil were sent to a separator, while washwater was recycled using an on-site water treatment unit. Treated gravel was re-used right on Correctional Service of Canada's premises in Ste-Anne-des-Plaines.

Now that the project is over, we can be proud and relatively happy about the results. Taking into account the contingencies and the need for compliance with laws and regulations, we can say that we have done our best.

If, however, we question ourselves and analyze our good deeds, we must wonder if we have really acted in the best interest of the environment. From a global viewpoint, there is still room for improvement.

Remediation of Newfoundland Coast Guard Sites

**Mr. Glenn Marshall
Environmental Officer
Technical Support Services Branch
Canadian Coast Guard**

PRECIS*

Canadian Coast Guard - Environmental Cleanup Program

The Canadian Coast Guard has identified the degree of environmental concerns present at 56 Marine Navigational Services (MNS) Facilities in the Newfoundland Region. Detailed assessments were required for each site to obtain an indication of the degree of contamination. The following assessments were completed prior to remediation activities being undertaken:

- Phase I - Environmental Audit/Baseline Site Assessment - 1994;
- Phase II/III - Site Investigation of MNS Facilities in 1995;
- Phase IV - Remediation Action Plan - 1995/96, and;
- Phase V - Risk Assessment - 1995/96.

After the completion of a Phase V - Risk Assessment, the criteria was established for the development of the Phase IV - Remediation Action Plan (RAP). The RAP and the Risk Assessment identified the level and location at which remediation activities should be completed. These activities merged with the established soil criteria in the CCME guidelines portrayed a realistic approach to the remediation action required at each site.

After a detailed evaluation of remediation alternatives, in-situ landfarming was chosen as the most cost effective method for remote CCG sites. The addition of the correct volumes of amendments such as fertilizer, lime and peat enable the most effective mixture to enhance the natural biodegradation of the hydrocarbon contaminated soil.

Peckford Island Site Cleanup

Of the 27 sites remediated to date a short presentation on the cleanup of the Peckford Island Lightstation on the NE Coast of Newfoundland is a typical example. The Peckford site had

* This precis by Glenn Marshall and Craig Wardlaw, WTI.

several contaminated areas which needed remediation and numerous structures which had to be demolished and removed. The contaminated areas included:

- the fuel storage area where spillage and leakage had occurred the chemical storage building where chemicals and fuel had leaked through the floor
- other areas where fuel had been spilled
- mercury contaminated soil

Each area had an individual remediation strategy. The fuel contaminated soils were bioremediated in-situ. The soil in this area is a very thin layer over bedrock so incorporating nutrients, amending agents and air by tilling was relatively easy. Grass seed was sown on the treatment areas. The mercury contaminated soil was removed in barrels to a central storage site in Newfoundland and then disposed through a licensed waste disposal company.

The soil which was biologically treated has had TPH levels reduced dramatically and cleanup criteria have been met.

Pilot Scale Bioremediation of Hamilton Harbour Sediments

Craig Wardlaw, WTI*

Introduction and Background

Hamilton Harbour is a heavily industrialized inland port. The major industry is steel production. Two large steel mills dominate the shoreline of the harbour. Iron ore, coal and other raw materials are shipped to the Harbour and various steel products are shipped out. In addition to the steel mills numerous other industries are located in Hamilton and use the port for shipping and a source of water.

For many years the discharges of all industries were not regulated or were incompletely regulated in Canada (up to about 1975). Industry discharged waste materials directly into the harbour and spills to the water were common. Stockpiles of iron ore and coal were not protected and wind and rainfall caused significant amounts of these to blow or wash into the water. Much of the discharged material settled out of the water column and built up in the sediments. Even though direct discharges to the harbour have been drastically reduced the sediments remain highly contaminated. Large areas of the harbour sustain no benthic life and the majority of the harbour has only pollution tolerant benthic species present.

The sediment in the highly contaminated areas is very oily and black. The oily material is generally referred to as "coal tar" although it is actually a mixture of coal tar, coal dust and other organic contaminants. The sediment is fine grained with a small proportion of debris (mainly iron ore nuggets). The chemical composition of the sediment is as follows:

Polycyclic aromatic hydrocarbons (PAHs)	800 - 15,000 mg/kg
Total organic carbon	10 - 30 %
Metals	
Zinc	1000 - 3000 mg/kg
Lead	100 - 600 mg/kg
Iron	2 - 20 %

In laboratory bioassay tests the raw sediment kills all benthic and aquatic organisms within a few hours.

Method

The pilot project was undertaken by Grace Dearborn Inc. (now called Grace Bioremediation technologies Inc.) of Mississauga, Ont. Sediment was dredged from the harbour using a specially designed dredge, was dewatered using settling and decantation and was delivered to the treatment area by barge. The Dearborn technology, named "Daramend", is best described as "pad farming".

* based on report prepared by Grace Dearborn Inc.

Sediment to be treated was spread out on a specially constructed treatment pad which prevents the escape of contaminants to the surrounding or underlying soil. The pad was lined with an impermeable plastic liner and the liner was covered with a layer of clean sand. Sediment was placed on top of the sand and allowed to dry to roughly 30% water. The pad was covered with a polyethylene greenhouse. Bacteria from the sediment were cultivated in the laboratory and subjected to bench scale tests to determine their ability to degrade organic contaminants. In this case the natural bacteria in the sediment were found to be excellent degraders of Polycyclic Aromatic Hydrocarbons and no additional bacteria were added. Dearborn added nutrients and a specially prepared organic amending agent which gave "body" to the sediment. The amending agent allows the sediment to hold more water and air, both of which are critical to the success of bioremediation. The sediment was mixed using common agricultural tillage equipment once every two weeks.

For this demonstration it was planned to treat two different types of sediment from Hamilton Harbour. Approximately 85 cubic metres of untreated sediment and 50 cubic metres of sediment pre-treated with calcium nitrate were dredged. The sediment pre-treated with calcium nitrate was from a site in the Harbour which had been injected with the calcium nitrate by the Limnofix In-Situ treatment. As well two distinct control areas of roughly 2 cubic metres each were to be set up on the treatment pad. The first was an untilled and unamended control. The second was a tilled but unamended control.

The pilot project began Oct. 9 1992. The treatment pad was constructed on vacant industrial land at Pier 26 donated by the Hamilton Harbour Commissioners.

Results

The Grace Dearborn project has to be considered a success. The overall level of PAHs in the sediment was reduced from over 1100 ppm to under 100 ppm. The simplicity and low cost of the Daramend technology make it an extremely attractive alternative to other forms of treatment. In addition Grace Dearborn is one of the few companies marketing a biological treatment technology which has defensible scientific data to back up their claims.

**Environmental Decommissioning of Beban Camp
Lyell Island, Gwaii Haanas National Park Reserve.**

**Liz Baker
Contaminated Sites Officer/Backcountry Manager
Public Works and Government Services Canada**

The environmental clean-up project on Lyell Island in Gwaii Haanas National Park Reserve is a prime example of the National Contaminated Sites Remediation Program. The Parks Canada project demonstrates the proactive decision making process integral to tackling a significant contaminated sites problem. Coordination and mediation between various government agencies, historical data sources and private consultants is essential. Most importantly, the Environmental Decommissioning of the site (formerly the Beban Logging Camp) illustrates a government process that identifies concerns, selects different solutions, allocates funding and prioritizes actions to produce the results intended by the Contaminated Sites Program.

Beban Camp is a former logging townsite and operations yard located at Powrivco Bay on Lyell Island within Gwaii Haanas National Park Reserve. The site was abandoned after a moratorium was placed on the island in 1987. This was a prelude to the island becoming incorporated as part of the Federal/Provincial Agreement to establish a National Park Reserve. During the closing phases of the Lyell Island Rehabilitation program (1992), the areas adjacent to the camp's former fueling and storage facilities were identified as heavily impacted with diesel, gasoline, heating oil and other petroleum hydrocarbon contaminants. Because these contaminants had pooled and penetrated deep within the soil horizon, they were not detected until the site was being actively rehabilitated. The site is adjacent to a freshwater supply and is frequented by commercial and recreational boats. It is also a base camp for research groups and will continue to be used in the future. Because the site consists of a popular protected cove, mooring and camping will continue as the park develops and the site fully regenerates. It is for these reasons that a five phased assessment/remediation program was initiated.

A Phase I assessment and historical review resulted in the designation of the site as a Class I Contaminated Site on the basis of the National Classification System (NCS). The NCS was designed to prioritize action levels in sites across Canada with respect to risk potentials related to contaminant type, hydrogeology, land use and exposure pathways. The Class I designation implied a high risk level and the need for further action.

The Phase II and III environmental assessments were conducted by a consultant (Seacor) and they performed an intrusive investigation of the area with an excavator and environmental sampling equipment. Laboratory results indicated Special Waste Levels of petroleum hydrocarbons, primarily diesel, at six separate locations at the site. It was projected that 10,000 cubic meters of impacted soils exceeded the Canadian Environmental Quality Criteria for Contaminated Sites (CCME) Parkland/Residential and BC provincial level B/Class 1 soils remediation criteria. The contamination plumes had migrated to the intertidal zone particularly at the location of the former fuel dispensing island.

An application was made to Conservation and Protection, Environment Canada for Orphan Site designation under the Orphan Sites Program. This federal Green Plan initiative provided funding for the cleanup of high risk designated sites in which no owner is held or found to be

accountable. This program allows for 50 % of the remediation costs to be recovered by Parks Canada.

Six remedial options were evaluated with respect to associated costs, schedule impact and relative long and short term environmental parameters. Several site specific design criteria were considered which included such factors as the remote location, limited access, lack of power supply and seasonal weather conditions. The consensus between Parks Canada and Conservation and Protection was to proceed with Phase IV Remediation, with in-situ Containment and Active Biological treatment.

This option provided a reasonable degree of containment with the ability to biologically degrade the contaminants to acceptable levels at an economically viable cost. The remediation system installation was scheduled to coincide with important respective fisheries and weather windows in the summer of 1992. A large 40 m X 80 m X 3 m cell was constructed to 2 m below grade and lined with a synthetic liner. The impacted soils from the various sites were placed into the cell along with an integrated control system consisting of recovery wells, nutrient mixing and aeration piping and tanks, pumps and vacuum fans.

The biological method involves a process called Bio-stimulation in which the populations of indigenous bacterial hydrocarbon decomposers are enhanced through the addition of oxygen and the optimization of nutrient and moisture levels. The complete cell is then encapsulated with a lined cover, landscaped and replanted with local vegetation to prevent the infiltration of precipitation and providing long-term security. After one season of operation, residual contaminant levels have been reduced by 75% of their original concentration.

Soil Analytical Results

Sample Id/ Date	Benzene (ppm)	Ethylene (ppm)	Toluene (ppm)	Xylene (ppm)	LH (ppm)	TEH (ppm)
Tank Farm Sept. 92	< 1	19	14	144	4550	13500
Bio-cell Oct. 93	< 0.05	5.3	0.6	73.6	1870	1890
CCME Parkland	0.5	5	3	5	N/A	N/A
B.C. Class 1	0.5	5	3	5	100	400

Note: ppm -parts per million
 LH -light hydrocarbons
 TEH -total extractable hydrocarbons
 CCME -Canadian Environmental Quality Criteria for Contaminated Sites. Report CCME-EPC-CS34, September 1991
 B.C. Class 1 -B.C. Environmental standard for parkland/residential land use November 21, 1989. Note: TEH may be increased to 1000 ppm by project closure.

Phase V Environmental Closure on the site was gained in 1994/95 and the cell was abandoned and allowed to return to natural background conditions with time. From a philosophical perspective, a contained in-situ active biological treatment program provides for a responsible stewardship approach to actively deal with hydrocarbon contaminated soils. The projected final cost for completion of the remediation was \$70 per cubic meter, 25% of the total cost per cubic meter was incurred as a result of its remote location. Despite the disadvantages of remote location, limited access, no power, and a phased decommissioning program, the project is achieving success within the estimated timeframe in a cost effective manner.