

APPENDIX I: Selecting a Remediation Process

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Selecting a Remediation Process for a Contaminated Area

Introduction

Remediation is the process during which a polluted area is cleaned of its contamination. For projects undertaken by the Blacksmith Institute, sites that require remediation are those that are the direct cause of human illness and those that are significantly impacting on human health. For a contaminated site, the selection of a remediation technology is based on the type of contamination that exists, whilst ensuring that the choice of technology is appropriate to the socio-economic climate of the region.

Major Considerations for Remediation Selection

Contaminated land is an area that contains concentrations of a chemical substance that are so great that the amount of the substance cannot be reduced by natural environmental processes. The contamination may be held in either of the following parts of the environment: the soil, water (surface or groundwater) or the air. Humans may be exposed to the contamination when they interact with a part of the environment that contains concentrations of the pollutant at toxic levels.

The choice of remediation process for a particular site requires the following considerations:

What is the type of contamination?

Which part of the environment is contaminated?

What is the objective of remediation?

What is the type of contamination?

In most cases, land is contaminated as a result of human activities, which may include:

Industrial processes, e.g. leather tanning, electronics production etc.

Mining of metal rich ores or fossil fuels

Waste disposal areas/landfills, or

Discharge of human sewage wastes

Waste is produced from all of the above processes, and is released into the environment as a liquid effluent, a solid waste, or as an atmospheric emission. The waste products released may contain a wide variety of chemical substances. In a majority of cases the most toxic agent is targeted.

Which part of the environment is contaminated?

Contaminants are found in either soil, water, or air. Contaminants that are transferred to humans in food products will originate in either the soil or the

water. The choice of remediation method is principally dependent on the part of the environment in which the contaminant is located.

If the soil is contaminated, it can be excavated and treated. If the contaminant is carried in water, the water can be pumped out and the contaminant removed using water treatment equipment.

Contaminants that are carried through the air generally need to be controlled at the source. For example, a toxic industrial air emission should be treated to remove its toxicity before being emitted into the environment, and in the case of lead in the atmosphere, the source control measure has been to eliminate the use of leaded fuels.

What is the objective of the remediation?

For the Blacksmith Institute projects, the purpose of remediation is to minimize adverse impacts on human health by preventing human interaction with the toxic pollutants. Not all polluted places need to be cleaned up 100% in order to prevent human interaction.

Methods such as *Capping* do not remove the contamination, but place a barrier on top of the polluted soil so that people cannot interact with the contaminated soils.

Alternatively the contaminant can be *Contained* by placing barriers into the ground across the flow path of the pollutants, thereby preventing the spreading of the pollution into areas where humans may be exposed.

Contaminant Classes and their Behavior in the Environment

The majority of remediation technologies are specific to certain classes of contaminants. In order to choose a suitable remediation technology, and to understand how the technology works, it is important to have some understanding of the different classes of contaminants and the way in which they behave in the natural environment.

Polluted discharges contain a variety of contaminants that undergo different chemical reactions in the environment. The suitability of a particular remediation technology is dependent on the way the target contaminant behaves. Some contaminants will react with the soil and become permanently attached to it, while other contaminants will migrate through the soil and dissolve or float on the groundwater.

Volatile Organic Compounds

At normal temperatures, Volatile Organic Compounds (VOCs) will evaporate from liquid to the air. If liquids containing VOCs are spilt onto the soil, they may bond to the soil particles. When they are released into the air, these chemicals can be inhaled.

VOCs are contained in Organic Solvents and Chlorinated Organic Solvents. Petroleum products also contain volatile chemicals that will evaporate into the air at normal temperatures. When a solvent or a petroleum product leaks into the ground, remediation processes that use air as the carrier can be used to remove the volatile portion of the contamination.

Non Aqueous Phase Liquids

These liquids are not easily dissolved in water. Petroleum products including oils and fuel are examples of Non-Aqueous Phase Liquids (NAPLs). The limited ability of fuel and oil to dissolve in water is noticeable when puddles of rain develop on a road. Visible streaks of fuel and oil can be seen floating on top of the water. A NAPL will behave in the same way when it reaches the groundwater. Depending on the density of the liquid it will either float, or will sink to the bottom of the water.

Other petroleum products include Paraffin, Crude Oils, Kerosene, Petroleum, Asphaltic Oils, Lubricants, Tars (PAH's) and Grease. These compounds contain many organic chemicals including benzene, toluene, ethyl benzene, xylenes (BTEX group), pentane, ethane etc. Organic chemicals can be degraded by soil microorganisms.

Heavy Metals

The majority of metal compounds will stick to soil particles. Metals that are released into the atmosphere from processes such as the burning of fossil fuels will eventually settle onto the ground. Metal contaminants that are released in liquid effluents are also likely to settle and become a soil contaminant.

Where the metal contaminated soil is close to the surface, there is a risk of human interaction with the contaminant. If the contaminant does not extend too deep, methods such as excavation and *ex-situ* soil treatment can be used to remove it. If the metal contamination is deep underground there is only a minimal risk of human interaction, thus there is a low risk.

However some metal contaminants can be found in forms that are soluble in water. These metal compounds can be found in ground or surface water and are very dangerous to humans. Soluble heavy metal contaminants can be swallowed, absorbed through the skin or taken up by plants or animals and then eaten by humans.

Organic Chemicals

An enormous amount of chemicals come under the heading of organic chemicals. Common organic pollutants are PAHs, PCBs, organic solvents, petroleum hydrocarbons, alcohols, ketones and aldehydes. Organic chemicals may also be used in pesticides. DDT is a chlorinated organic compound.

Organic pollutants can be degraded by the action of microorganisms in the soil and water. However, when the concentrations of organic pollutants are toxic to humans, it is likely that the concentrations are toxic to microorganisms also. If organic contamination is high, remediation technologies that can physically extract the contamination from the ground are required.

Choice of Remediation Technology

Detailed and specific classification of contaminants and their behavior requires the expertise of scientists who have a broad knowledge of chemistry and access to good quality sampling equipment. Similarly, the final choice of remediation process should also be done by a professional organization that have the experience, resources and expertise to be able to assess the feasibility and appropriateness of different remediation options.

However it is important for Blacksmith representatives to have some knowledge of the choice of remediation technologies that are available. Table 1,2,3 and 4 provide a description of the different remediation technologies along with their inherent advantages and disadvantages. The aim of the tables is to provide the user of this manual with an intermediate understanding of the types of remediation methods that are available and the particular circumstances in which each method is applicable.

Other Important Considerations: Local Socio-Economic Climate

There are issues other than the scientific and technical considerations that affect the choice of technology. Issues such as social acceptance and the suitability of the technology to the socio-economic climate of the region are also considerations that Blacksmith representatives should be aware of when faced with the prospect of remediating a site.

Highly technological solutions to remediation projects are not always the most appropriate solutions, particularly in developing countries. Highly technical methods require specific equipment and highly skilled people to operate the equipment, both of which may not be readily available in a developing nation. Where appropriate, the use of local materials and labor should be incorporated into the remediation. This consideration will not only increase the social acceptability of the solution, but will more often than not compare favorably in terms of cost than when using imported technologies.

Additionally, remediation does not mean that the contaminant has to be 100% removed from the site. Methods such as containment and ongoing site management can also be effective solutions.

As the expected cost of a project is a significant factor which affects the willingness of local authorities and local agencies to participate in the rehabilitation of contaminated land, the use of innovative ideas to cut the cost of a project will result in more projects achieving success.

It should be remembered that the best technical solutions are not always the most appropriate solutions, particularly in a developing country with limited expertise and resources. With a good knowledge of both technical and non-technical remediation methods, combined with a creative and insightful mind, solutions that are economically viable and appropriate to the socio-economic climate of the region can be delivered.

Remediation Processes

The following tables provide a list of the different remediation processes that are available. The tables provide a brief description of each process, guidelines as to when the process should be used, the inherent advantages and disadvantages of each process and estimates of the cost of each process. The aim of the tables is to provide the user of this manual with an intermediate understanding of the types of remediation methods that are available and the particular circumstances in which each method is applicable.

Remediation Processes Using Air or Water

Table 1 lists the common remediation methods that use air or water to extract the contaminant from the ground. Air is used as a carrier for *volatile* pollutants and water is used as a carrier for *soluble* pollutants. Once the pollutant has been removed from the ground, the polluted medium (air or water) needs to be passed through a suitable air or water treatment system. Treatment will either destroy the pollution or will condense the pollutant into a waste product that can be disposed of in a controlled landfill. According to Nyer et al., air treatment systems and their operation and maintenance can cost up to \$72 000 per year.

Table 1: Remediation Process That Use Air or Water as the Carrier

<u>Name of Method</u>	<u>Description of Process</u>	<u>When should the process be used</u>	<u>For Which Pollutants</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Costs</u>
Pump and Treat	Groundwater is extracted from the earth through a pumped well. The contaminated water is then treated on the surface using water treatment equipment.	Suitable when there is widespread contamination of groundwater. When the pollutants that need to be treated are highly soluble in water.	Dissolved heavy metals Dissolved organic contaminants Ketones Alcohols	Will cause a rapid decline in the concentration of the contaminant during the early stages of the project. Effective in stopping the movement of a contaminant plume.	Is not effective for contaminated areas that are not permeable to water. Cannot remove NAPL's or metals that are attached to the soil. May not be able to reduce the concentration to very low levels. Can take between 5 and 20 years.	Water treatment equipment is the major capital cost. Major ongoing costs are associated with the operation and maintenance of the pumps and water treatment unit.

Soil Vapour Extraction	A pipe is inserted into the ground which passes through the contaminated region. A vacuum is then created in the pipe and the vapors are sucked out of the ground. The contaminated is removed in an air treatment unit.	Suitable in locations where contaminants have being spilt and are not widely dispersed. When the contaminant is volatile.	VOCs Petrochemicals Moderately suitable for chlorinated organic compounds.	Relatively short clean up period of 6 – 24 months. Increases oxygen supply to promote biodegradation. Rapidly removes contaminant when the concentrations are high.	Not suited to heavy organic compounds or metals. Not suited to highly soluble pollutants. Has a high operational and maintenance cost.	\$18,000 - \$35,000 design and installation ¹ . \$55/tonne O/M costs ¹ .
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Air Sparging	Air is pumped into the lower region of the water table. As the air bubbles rise to the surface of the water table, dissolved VOC's are stripped from the water. It is combined with a vapor extraction unit to remove the contaminant from the ground and contain it for treatment.	At locations where the contaminant is in high concentrations. At locations that are a significant distance from large buildings and other heavy structures. Is suitable when the contaminant exists in a gaseous state.	BTEX Group Chlorinated Solvents Most petroleum hydrocarbons.	Can be used to deliver oxygen to the soil to enhance bioremediation Clean up times of less than 12 months have been reported to achieve groundwater standards.	Not suitable for delivery of nutrients including nitrogen and phosphorus. Not suitable for heavy petroleum products that are neither volatile nor strippable. Quantities of air injected for stripping may cause soil instability which may be a problem if used near buildings.	Is renowned for being significantly cheaper than other conventional techniques however it is a new approach that has not being proven in a number of circumstances. Not economical in large sites where a number of deep bores need to be dug.
Bioventing	Oxygen is supplied to the contaminated region in order to create aerobic conditions so that microorganisms can degrade the contaminants. Enough air is	If there are suitable microorganisms present in the soil and the contaminant is not toxic to them. If the contaminant is above the groundwater table.	A majority of organic contaminants.	Has been shown to reduce contaminant concentrations quite rapidly. Air can deliver oxygen more rapidly and in much greater quantities than water can.	Nutrients essential for microbial growth cannot be successfully injected in air but need to be carried in a liquid such as water, which requires an additional water delivery	Capital costs can vary between \$30k to \$50k ³ . Costs of analytical testing to determine the suitability of conditions for microbial

	provided to keep the contaminated region aerobic, but not enough to push contaminated air out of the ground, such as is done in air sparging.	If the soils at the site are stable and are of suitable pH, temperature and moisture conditions to sustain microbial growth.			network. Needs to be controlled to prevent movement of the contaminant vapor out of the soil.	degradation can range from \$10k to \$50k ³ . \$20/cubic meter O/M costs ¹ .
Vacuum Enhanced Recovery	Utilizes both water and air as a carrier for pollutants. Creates a large pressure change using a powerful vacuum which increases the movement of groundwater. Air is also utilized to reach the pollutant in areas that are not permeable to water (e.g. clay). Requires both water and air treatment on the surface.	Suitable if rapid removal of a localized spill is required.	NAPL's VOC's Chlorinated VOC's	Allows fast recovery of pollutants. Acts over a wider zone than vacuum extraction. Powerful enough to extract almost all vapours from the soil zone. Can remove both dissolved pollutants and volatile pollutants that are attached to the soil. Increases oxygen content for biodegradation.	Only suitable to soils where air and water can easily flow through the soils. Requires pilot studies to test its applicability.	Allows fast recovery of pollutants, which can improve its cost effectiveness. Dependent on whether a one or two pump system is required.

Containment Remediation Methods

Containment methods are used to control the spreading of a contaminant throughout the environment. When the contaminant is a soil pollutant, containment methods such as capping can be used to prevent human interaction with the contaminant. When the contaminant is located in the groundwater, the pollutant can be intercepted and removed by placing a reactive barrier across the flow path of the groundwater to prevent the contaminant spreading further.

Table 2: Containment Remediation Methods

<u>Name of Method</u>	<u>Description of Process</u>	<u>When should the process be</u>	<u>For Which Pollutants</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Costs</u>
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Horizontal Trench Sparging	A trench is dug into the groundwater table. An air delivery pipe is placed at the bottom of the trench and an air extraction pipe is placed at the top. Pollutants are removed via the circulation of air which is then treated on the surface.	used Suitable if the contaminant is not widely dispersed throughout the ground water. Is effective close to the source of the pollution, before the contaminant has had time to spread.	BTEX group Most petroleum hydrocarbons Chlorinated solvents Biodegradable organic contaminants	Does not need to run continuously due to the slow velocity of groundwater. Nutrients can be added to increase biodegradation and natural attenuation downstream.	Need to deal with contaminated soils that are extracted from the construction of the trench.	Accumulate a high cost at greater than 30 feet deep. Energy costs are reduced as the machinery does not need to run continuously.
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Reactive Barriers	A reactive material is placed across the flow path of the contaminated groundwater. As the pollutant flows through the barrier, chemical reactions occur that change the properties of the contaminant into less dangerous forms. It can be combined with an impermeable barrier, which acts as a funnel to capture a wider amount of the groundwater plume.	Can be positioned at the perimeter of an industrial site to intercept the path of a contaminant before its reaches residential land. To prevent the spreading of a groundwater contaminant.	Chlorinated solvents Metals, Inorganics Radionuclides Chlorophenols	Good for shallow groundwater plumes. Can be combined with air sparging to remove VOC's, and BTEX pollutants.	Is only suitable to soluble contaminants. Impracticable for large and deep plumes. It is a new technology whose long term performance has not been tested for issues such as clogging or loss of reactivity of the surface. May require periodic removal of the active surface.	Initial capital expense is the major cost. Ongoing operation and maintenance costs are minimal.
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<p>Reactive Zone Remediation</p>	<p>A number of wells are dug across the path of the contaminated groundwater. Products are released into the ground through the wells, creating a reactive pool in the groundwater.</p>	<p>Can cope with larger plumes than treatment barriers can. Is generally used to speed up natural attenuation processes that occur after the bulk of the contamination has been removed by a separate process.</p>	<p>Metals Chlorinated VOC's, BTEX Ketones.</p>	<p>Speeds up the natural attenuation processes. Can be used at the perimeter of a site as a control barrier. Does not require any above ground treatment</p>	<p>If soil contamination is widespread, it may require a large number of wells to be dug.</p>	<p>Cost is determined by the amount of wells that are required. Requires initial assessment and pilot studies to determine what products to inject into the reactive zone.</p>
<p>Capping</p>	<p>A layer of earth is placed on top of the contaminated area to prevent direct human contact with the contaminant. The cap can be made of concrete, a liner (geo-membrane) or of soil. Plants can also be a part of the capping layer.</p>	<p>Should be used if the contaminant is immobile and where there is no risk of the ground water becoming contaminated.</p>	<p>All insoluble contaminants.</p>	<p>Easily installed Low O/M costs</p>	<p>The long term liability of the contaminants is not solved. Groundwater monitoring may be required. Some soil may need to be removed prior to capping which creates a disposal problem.</p>	<p>Is a very cost effective option.</p>

Solidification/ Stabilization	A solution is added to the contaminated soil, which changes the chemical structure of the contaminant to a form in which it is no longer toxic, or to a form in which it is no longer mobile. The soil can be removed from the ground and relocated to a different place, or left in the ground in its <i>non-reactive</i> state.	If the soil is not highly contaminated and where there is plenty of time in which to complete the remediation. Where the contaminant is easily immobilized.	Metals Inorganics	Can treat large areas of contaminated soils.	Cannot treat contamination that extends deep into the soil. A long time period is required.	\$50 - \$150/tonne O/M costs ² .
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Bioremediation and Natural Remediation Processes

Bioremediation and natural remediation processes utilize natural environmental processes to treat contamination. Microorganisms such as bacteria and fungi have the ability to break down contaminants in the environment. Other natural processes such as those in a wetland and the uptake of soil nutrients by plants can also be used to remove contaminants from the environment. By using Bioremediation and natural remediation processes, the total cost of a project can be minimized; however the time taken to reach completion may be considerably longer than for an active remediation/treatment solution.

Table 3: Bioremediation and Natural Remediation Processes

<u>Name of Method</u>	<u>Description of Process</u>	<u>When should the process be used</u>	<u>For Which Pollutants</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Costs</u>
Bioremediation	Microbes such as bacteria, fungi and algae consume organic compounds from the	If the concentration of the contaminant is not overly excessive. If there are	Heavy metals NAPL's BTEX Organic compounds Petroleum	A wide variety of bacteria are available that are suited to most purposes.	Microbes are susceptible to changes in environmental conditions such as	Much cheaper than full scale active methods. High costs are involved in the

	<p>environment in which they live. Contaminants may be consumed or fixed into non-reactive states by the action of microbes. Bioremediation requires an active component to regulate the growing environment of the microbes.</p>	<p>microbes present in the soil that are capable of degrading the contaminant.</p>	<p>hydrocarbons Chlorinated solvents</p>	<p>Earth intrusion costs are minimal. Above ground active treatment systems are not required.</p>	<p>pH, temp and nutrient availability, moisture. If environmental conditions vary, they can die rapidly. Slower than active remediation processes. Susceptible to excessive concentrations of heavy metals, chlorine compounds and some organic pollutants.</p>	<p>initial sampling stage that involves microbial tests and environmental tests.</p>
<p>Natural Attenuation</p>	<p>The natural degradation of pollutants that occurs as a result of microbial activity. Does not have an active component.</p>	<p>Is suitable when the pollutant concentrations are too low for an active remediation process to be a viable option. Is most often used after an active process has been used to eliminate the majority of a pollutant's concentration.</p>	<p>Can fix heavy metals NAPL's BTEX Organic Compounds Petroleum hydrocarbons Chlorinated Solvents.</p>	<p>Has the ability to achieve the final concentration goals. Is the best method when the level of contaminant is low.</p>	<p>Slow compared to active methods.</p>	<p>Does not have an inherent cost. Associated costs include initial testing and ongoing monitoring costs.</p>
<p>Phyto-remediation</p>	<p>Plant species that have the ability to withstand high concentrations of metals are planted on the contaminated site. The plants effectively remove the pollutant from</p>	<p>Can be used to remove shallow metal contamination. Can be used as a part of a soil capping layer.</p>	<p>Metals</p>	<p>Is extremely cheap in comparison to active methods. High concentrations in plants may be viable for metal smelting.</p>	<p>Is not suitable for remediating pollution from deep soil layers. Plants may be consumed by animals or humans if not properly managed. The use of this process is dependent on the availability of</p>	<p>Has a low implementation cost and minimal ongoing costs, however costs of disposing of the end plants at their end of life needs to be considered.</p>

	the ground by accumulating the pollutant in the plant itself. The plants can then be disposed of.				suitable plant varieties for the climate of the region.	
Wetlands	Remediates water soluble pollutants through a number of different processes including microbial degradation, plant uptake and immobilization in sediments.	Most suited to removing soluble contamination from contaminated surface water sources.	Metals Organic material	Wetlands also have the potential to treat sewage and other organic wastes through the action of microbes, algae sedimentation and filtration.	Without proper management, the wetland may used as a water source for bathing or drinking, thereby becoming a source of contamination in itself.	Initial capital construction costs are significant. Ongoing costs are minimal.

Ex-Situ Remediation Methods

Ex-situ remediation requires the excavation of the contaminated soils and the subsequent treatment of the waste out of the ground. Excavation is applicable in areas that have stable ground and low groundwater tables. If excavation is viable, the following soil remediation methods can be utilized.

Table 4: Ex Situ Soil Remediation Technologies

Name of Method	Description of Process	When should the process be used	For Which Pollutants	Advantages	Disadvantages	Costs
Soil Washing	The contaminant is removed from the soil by washing the soil in an appropriate solution. The contaminant accumulates in the slurry end-product that is collected for disposal.	If the soil contaminant has not spread too deeply into the soil layers. To treat soil that is removed to make way for a capping layer.	Semi volatile organic compounds Petroleum hydrocarbons Inorganic chemicals Chlorinated organic compounds Petroleum	Relatively short clean up time. The equipment is transportable.	Relatively high O&M costs. Safe disposal of the soil slurry end products is required.	\$40 - \$120 / tonne O/M Costs ² .
Solid Phase	Contaminated soil is	Is suitable for	Petroleum	Low capital cost	A large amount of surface	Less than \$110/tonne

Biological Treatment	excavated from the earth and is placed in piles above the ground. The active process is bioremediation, which is controlled by regulating the environmental conditions inside the piles.	organic contaminants that degrade better in the presence of oxygen.	hydrocarbons VOC's	and simple to implement.	area is required. Air emissions may require treatment. Remediation process may take a long time.	inclusive of design, installation, O/M and excavation ² .
Incineration	The excavated soil is heated to temperatures between 870°C and 1200°C to combust VOC's and Organic compounds.	If energy is not scarce. Preferable in locations where incineration plants are already operational.	VOC's Organic compounds	Is a permanent solution. Has a wide range of applicability.	Metals are difficult to treat. Has a high capital cost. Requires control of air emissions.	\$100 - \$850/tonne O/M costs ² .
Vitrification	A temperature of between 1400°C and 2000°C is applied to the soil. The immense heat causes the metal contaminants to bind in the 'rock like' vitreous product that is created. Organic contaminants are destroyed by the immense heat.	If the contaminants are inorganic Where energy sources are readily available.	Inorganics Metals Semi volatile organic compounds NAPL's	Creates a hard product that is highly immobile.	End product needs to be disposed of. Requires control of air emissions during process.	\$550/tonne inclusive of design, implementation, excavation and O/M.

Useful Weblinks

Remediation Methods

Source: Environment Canada: Ontario Region

Web Address: http://www.on.ec.gc.ca/pollution/ecnpd/contaminassist_e.html

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