

Distr.
LIMITED
E/ESCWA/ENR/2002/WG.1/4
14 March 2002
ORIGINAL: ENGLISH



United Nations Economic and Social
Commission for Western Asia



Federal Institute for Geosciences
and Natural Resources

Regional Training Workshop on the Application of
Groundwater Rehabilitation Techniques to Different
Hydrogeological Environments in the ESCWA Region
Beirut, 18-22 March 2002

ECONOMIC AND SOCIAL COMMISSION
FOR WESTERN ASIA
28-03-2002
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SOIL AND GROUNDWATER REMEDIATION TECHNIQUES AN OVERVIEW

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makes obvious that due to financial constraints needs and goals have to be formulated. In this process, also the limitations of the technical possibilities to achieve a remediation goal have to be considered in a realistic manner together with the limits due to the available financial means.

Table 1: Sources of groundwater quality deterioration

Problems originating on the land surface

- infiltration of contaminated surface water
- land disposal of solid and liquid waste materials
- stockpiles, tailings, and spoil
- dumps
- disposal of sewage and water-treatment plant sludge
- salt spreading on roads
- animal feedlots
- fertilizers and pesticides
- accidental spills
- particulate matter from airborne sources

Problems originating above the groundwater table

- septic tanks, cesspools, and privies
- surface impoundments
- landfills
- waste disposal in excavations
- leakage from underground storage tanks
- leakage from underground pipelines
- artificial recharge
- sumps and dry wells
- graveyards

Problems originating below the groundwater table

- waste disposal in wet excavations
- agricultural drainage wells and canals
- well disposal of wastes
- underground storage
- secondary recovery
- mines
- exploration wells and test holes
- abandoned wells
- water supply wells
- groundwater development

2. General reflections on groundwater remediation approaches

In cases of contamination of groundwater European legislation calls for action: either remediation, at least containment of the pollutants, or use-oriented mitigation of damage. Affected

is not only the emission source, but also the resulting plume. The polluted groundwater theoretically has to be cleaned up even if it does not serve for drinking water purpose.

Remediation can be defined as "the process by which health or environmental risks associated with the presence of contamination are reduced to an acceptable and pre-defined level". Technologies moving a problem around (in other environmental compartments) are unwelcome in our times.

In most remediation schemes, all too often the geological features of the subsurface are largely ignored and little understood, and most of the effort is involved with the design and construction of engineering structures. The important point to consider, however, is that groundwater remediation activities require dedication of sufficient resources to understand site conditions. Remediation technologies utilize techniques derived from interrelated disciplines of geology, hydrology, geochemistry, microbiology, engineering, construction, and agronomy.

Groundwater remediation and site cleanup can be solved successfully only basing on a serious site-specific investigation. Before starting remediation activities it is absolutely necessary to obtain enough information on the circumstances of the contamination. The target of remedial investigations and feasibility studies must be: knowledge on the company in question handling with hazardous substances in the past, detailed geological/hydrogeological characterization of the unsaturated and saturated zones of the aquifer(s) and properties, behavior and three-dimensional distribution of the pollutants in the underground, and, very important, the mass of contaminants to be removed (fig. 1).

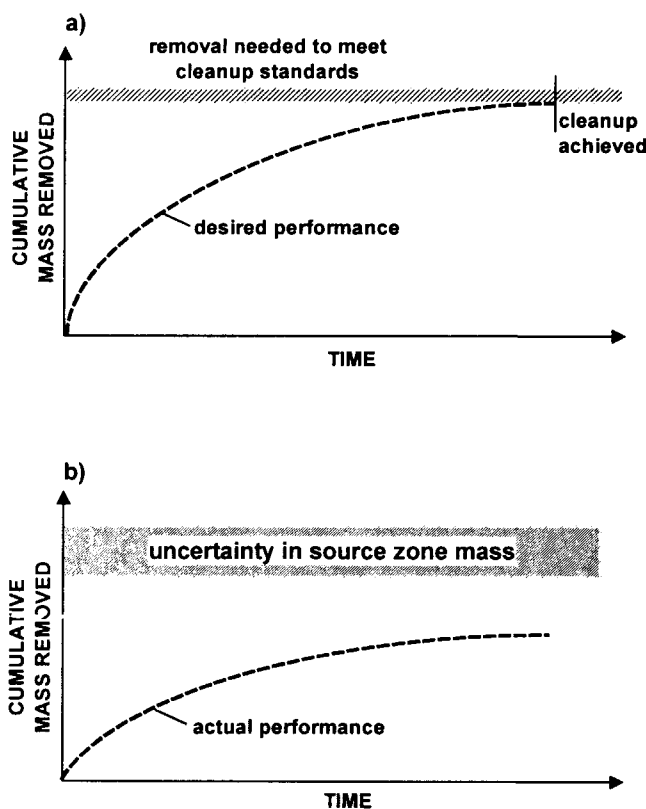


Figure 1: Graphical concepts for progress paths towards DNAPL source zone restoration:
a) the ideal case – containment mass in source zone is known and mass removal or destruction is fully effective,
b) the typical field case – the containment mass is not known and mass removal technology performance is not 100 % effective.

Data requirements for soils, which are inherently variable in their physical and chemical characteristics and therefore will result in variability in the distribution of contaminants, refer

mainly on information about soil particle-size distribution, soil homogeneity and isotropy, bulk density of soil, soil permeability, soil moisture, pH value, redox potential, octanol/water partition coefficient (K_{ow}), humic content, total organic carbon (TOC), biochemical oxygen demand (BOD) and chemical oxygen demand (COD), presence of oil and grease, and availability of sufficient electron acceptors, one of the major determining factors in the fate of biodegradable contaminants. In view of groundwater, additional data include water chemistry, average rate of groundwater flow (estimated from the hydraulic conductivity, hydraulic gradient, and effective porosity), safe aquifer yields and boundary conditions (the last two parameters require that pumping tests be conducted).

In connection with cleanup of a contaminated groundwater body the famous question is "How clean is clean?". The answer is very difficult. What is the acceptable groundwater quality? The natural, the site-specific geogenic background, allowing unrestricted use of the water? The diffuse environmental contamination background? Maximal concentrations of the groundwater components equal to drinking water standards? A restoration of contaminated groundwater at least to drinking water standards is the goal at most sites and expected by the public. Eventually, this goal makes necessary a management of water and a remaining risk has to be controlled.

In practice one must find a compromise solution between four diverging remediation philosophies:

- the protected medium principle (which includes the idea of multi-using),
- the utilization principle,
- the technical feasibility principle, and
- the economic principle.

With regard to „remediation“ one can differ between decontamination in a narrower sense (elimination of the pollutants of the affected environmental compartment) and containment (isolation of the hazardous substances by a hydraulic and/or geotechnical barrier from the medium to be protected, e.g. groundwater). With view of the remedial technologies we distinguish between thermal, physical, chemical, and microbiological processes (fig. 2).

There are in-situ techniques (in-ground treatment) and on-site/off-site-techniques (above-ground or ex-situ treatment, without/with transport of the medium to be treated). The medium can be soil, gas resp. soil gas, or groundwater. This paper is dealing only with groundwater and partially with soil and soil gas and predominantly with organic pollutants.

Proven, emerging or experimental in-situ groundwater and soil remediation technologies (as compared to the standard "pump-and-treat" approach for groundwater, or soil excavation and treatment) are pointed out. Emphasis is put on pump-and treat, in-situ bioremediation, pneumatic techniques (e.g. soil gas suction) and containment procedures.

Only a single technique or a train (combination) of techniques of which the efficiency is verifiable and is thoroughly controlled is acceptable.

The question of where remediation efforts should put on, relies upon three strategies. First, one must know, whether there has been a release of contamination to the environment though its amount and timing may remain in question. The second remediation concept concerns the potential transport pathways from the point of release to the point of exposure to the general population. The third possibility to start remediation activities is the potentially given risk to the population (fig. 3).

Technologies		Techniques
Remediation	Thermal technologies	burning/combustion pyrolysis
	Physical technologies	soil washing extraction active hydraulic technique pneumatic technique electrokinetic technique
	Chemical technologies	groundwater treatment soil treatment, in-situ soil treatment, on-/off-site
	Microbiological technologies	biopiles/composting bioreactors in-situ procedures
Containment	Containment technologies	encapsulation (surface cap, vertical walls, bottom sealing) immobilization passive hydraulic/pneumatic techniques

Figure 2: Types of remedial technologies/techniques – general overview.

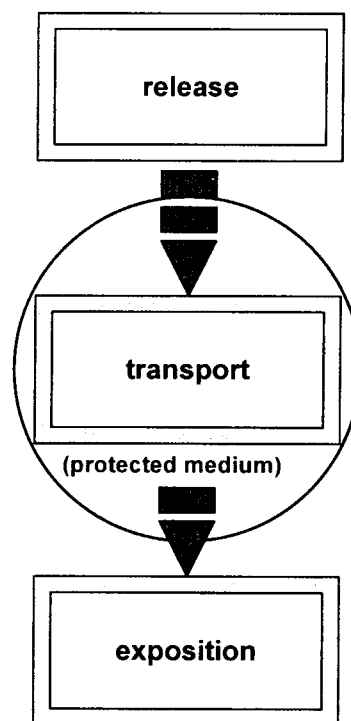


Figure 3: Assessment of contaminant effects and remediation strategies.

Regardless of the remediation approach, any source or sources that continue to contaminate the groundwater should be removed, isolated, or treated. Note that aquifer clean-up consists of several basic activities. One activity is the removal of any remaining free product. The more organic liquid can be removed, the more effective the groundwater remediation will generally be. When mobile or residual liquid phase is present, remediation is likely to be very difficult and may require pumping for hundred of years. A second activity is the removal of contami-

nants remaining in the vadose zone. If this latter activity is not carried out, water infiltration through the unsaturated zone will continue to leach the contaminants into the groundwater. The third and most important activity is the remediation of the contaminated aquifer itself.

3 Treatment technologies and their applicability to specific contaminants and media

Regardless from technical and geologic site-specific conditions, the groundwater remediation techniques which can be distinguished between established and emerging ones must be related to different types of contaminants. Roughly, eight groups have to be considered (table 2).

Table 2: Contaminant groups

- | |
|--|
| <ul style="list-style-type: none"> - Nonhalogenated volatile organic compounds - Halogenated volatile organic compounds - Nonhalogenated semivolatile organic compounds - Halogenated semivolatile organic compounds - Fuels - Inorganics - Radionuclides - Explosives |
|--|

Further, the remediation approaches and potential techniques must base on their applicability to the media to be treated, namely soil, groundwater, and air emissions and off-gases.

Remedial technologies capable of treating a contaminant group are presented in a technology screening matrix for each of the eight contaminant groups, documented in the annex. The treatment process groups documented include the following 14 treatment areas (table 3).

Table 3: Treatment areas for soil, groundwater, and gas

- | |
|---|
| <ul style="list-style-type: none"> - In-situ biological treatment for soil - In-situ physical/chemical treatment for soil - In-situ thermal treatment for soil - Ex-situ biological treatment for soil - Ex-situ physical/chemical treatment for soil - Ex-situ thermal treatment for soil - Containment for soil - Other treatments for soil - In-situ biological treatment for groundwater - In-situ physical/chemical treatment for groundwater - Ex-situ biological treatment for groundwater - Ex-situ physical/chemical treatment for groundwater - Containment for groundwater - Air emissions/off-gas treatment |
|---|

A general classification of remedial technologies with their relationship is given in figure 4. In connection with the annex a brief overview of these treatment processes is presented in the following chapter 4. The most commonly used technologies are discussed in chapter 5, the major emphasis is on most popular and successful alternatives for handling groundwater contamination problems especially with view of organic contaminants.

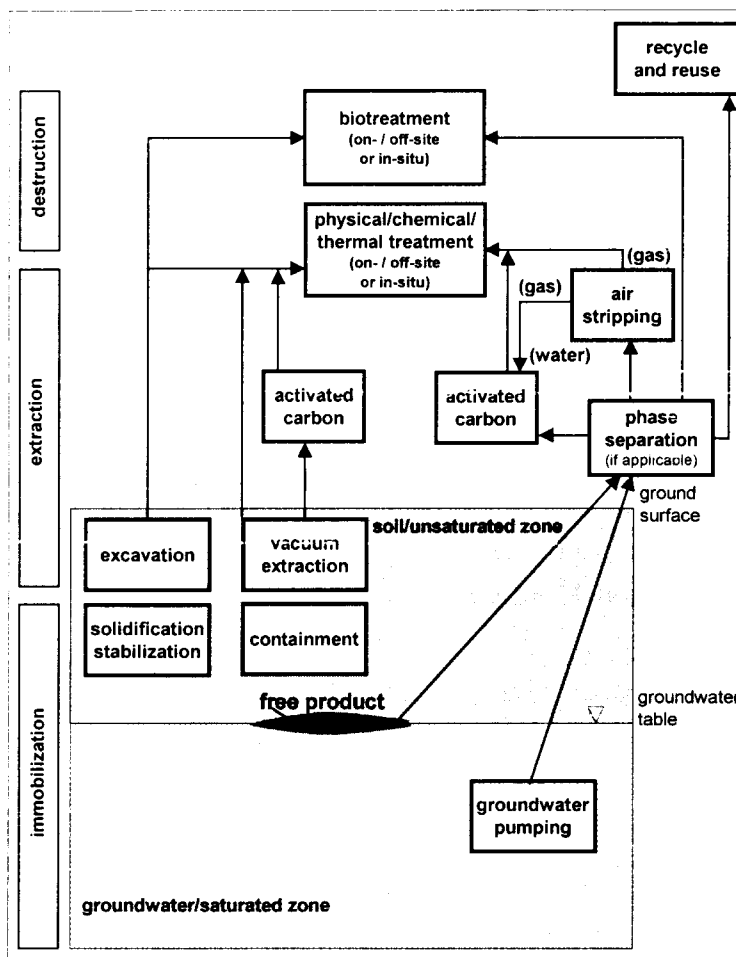


Figure 4: Classification of remedial technologies.

4. Brief overview of pollutants and treatment technologies

4.1 Nonhalogenated and halogenated volatile organic compounds

Typical nonhalogenated VOCs (excluding fuels, BTEX, and gas phase contaminants) include among other things acetone, aminobenzene, methanol, ethanol styrene, or vinyl acetate. Their importance in connection with significant soil and groundwater contaminations is only small. Typical halogenated VOCs are e.g. 1,1,1-trichloroethane, dichloromethane (methylene chloride), trichloroethene, tetrachloroethene, carbon tetrachloride, chloroform, or fluorotrichloromethane (Freon 11). Usually, the VOCs with attached chlorine atoms are groundwater contaminants, fluorine, bromine, and iodine halogens play a minor role.

Sites where volatile organic compounds (VOCs) may be found include burn pits, chemical manufacturing plants or disposal areas, disposal wells and leach fields, electroplating/metal finishing shops, firefighting training areas, hangars/aircraft maintenance areas, landfills and burial pits, leaking collection and system sanitary lines, leaking storage tanks, waste disposal areas, oxidation ponds/lagoons, paint stripping and spray booth areas, pesticide/herbicide mixing areas, solvent degreasing areas, surface impoundments, and vehicle maintenance areas.

Subsurface contamination by VOCs potentially exists in four phases:

- gaseous phase: contaminants present as vapors in unsaturated zone,
- solid phase: contaminants in liquid form adsorbed on soil particles in both saturated and unsaturated zones,
- aqueous phase: contaminants dissolved into pore water according to their solubility in both saturated and unsaturated zones,
- immiscible phase: contaminants present as non-aqueous phase liquids (NAPLs) primarily in unsaturated zone.

Insoluble organic contaminants may be present as NAPLs. Dense NAPLs (DNAPLs) have a specific gravity greater than water and will tend to sink to the bottom of aquifers. Light NAPLs (LNAPLs) will float on top of groundwater. In addition, DNAPLs and LNAPLs may adhere to the soil through the capillary fringe and may be found on top of water in temporary or perched aquifers in the vadose zone.

Soil vapor extraction, thermal desorption, and incineration are the presumptive remedies for sites with VOC-contaminated soil.

Soil vapor extraction is the preferred presumptive remedy. It is an in-situ unsaturated (vadose) zone soil remediation technology in which a vacuum is applied to the soil to induce the controlled flow of air and remove volatile and some semivolatile contaminants from the soil. The gas leaving the soil may be treated to recover or destroy the contaminants, depending on local and state air discharge regulations. Groundwater extraction pumps may be used to reduce groundwater upwelling induced by the vacuum or to increase the depth of the vadose zone. Air injection may be effective for facilitating extraction of deep contamination, contamination in low permeability soils, and contamination in the saturated zone.

In cases where soil vapor extraction will not work or where uncertainty exists regarding the ability to obtain required cleanup levels, thermal desorption may be the most appropriate response technology.

In a limited number of situations, incineration may be most appropriate. Incineration uses high temperatures, 870 °C to 1,200 °C, to volatilize and combust (in the presence of oxygen) organic constituents in hazardous wastes. For incineration of halogenated VOCs, off-gas treatment is needed to neutralize the acidic gas as the products of oxidation.

Bioventing, another common technology, uses a similar approach to vapor extraction in terms of equipment type and layout but uses air injection rather than extraction and has a different objective. The intent of bioventing is to use air movement to provide oxygen for aerobic degradation using either indigenous or introduced microorganisms. While some organic materials are usually brought to the surface for treatment with the exhaust air, additional degradation is encouraged in-situ.

The most commonly used technologies to treat VOCs in groundwater are air stripping, often with additional air sparging, and carbon adsorption. These are both ex-situ technologies requiring groundwater extraction.

Air stripping involves the mass transfer of volatile contaminants from water to air. For groundwater remediation, this process is typically conducted in a packed tower or an aeration tank. The generic packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated water over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect decontaminated water.

Air sparging is an in-situ technology in which air is injected through a contaminated aquifer. Injected air traverses horizontally and vertically in channels through the soil column, creating

an underground stripper that removes contaminants by volatilization. This injected air helps to flush (bubble) the contaminants up into the unsaturated zone where a vapor extraction system is usually implemented in conjunction with air sparging to remove the generated vapor phase contamination.

Liquid phase carbon adsorption is a full-scale technology in which groundwater is pumped through a series of vessels containing activated carbon to which dissolved contaminants adsorb. Carbon is "activated" for this purpose by processing the carbon to create porous particles with a large internal surface area.

Other fairly common technology used in separating contaminants from groundwater is membrane pervaporation. This process uses permeable membranes that preferentially adsorb volatile organic compounds from contaminated water. Treated water exits the pervaporation module, while the organic vapors travel from the module to a condenser where they return to the liquid phase.

Three technologies that are most commonly used to treat nonhalogenated VOCs in air emissions/off-gases are carbon adsorption (the adsorption process is comparable with that of treating contaminated groundwater), catalytic oxidation (VOCs are thermally destroyed at temperatures typically ranging from 200 to 350 °C by using a solid catalyst), and thermal oxidation (equipment is used for destroying contaminants in the exhaust gas, thermal oxidation units are typically single chamber, refractory-lined oxidizers equipped with a propane or natural gas burner and a stack; operating temperatures range from 450 to 550 °C).

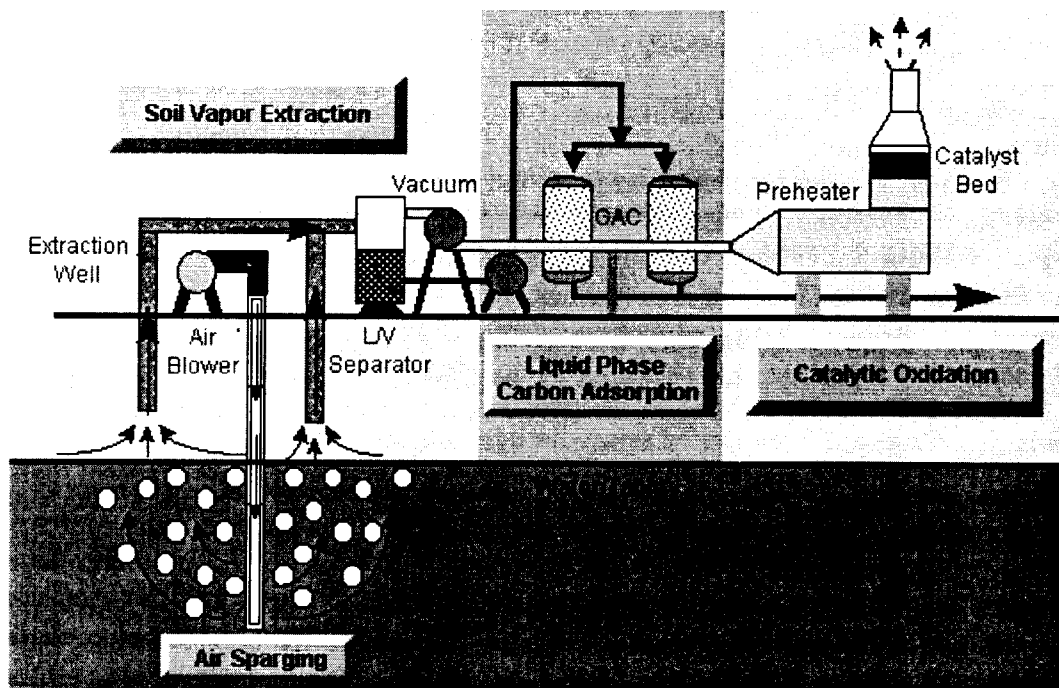


Figure 5: System diagram of a common treatment train for VOCs (after van DEUREN et al. 1993).

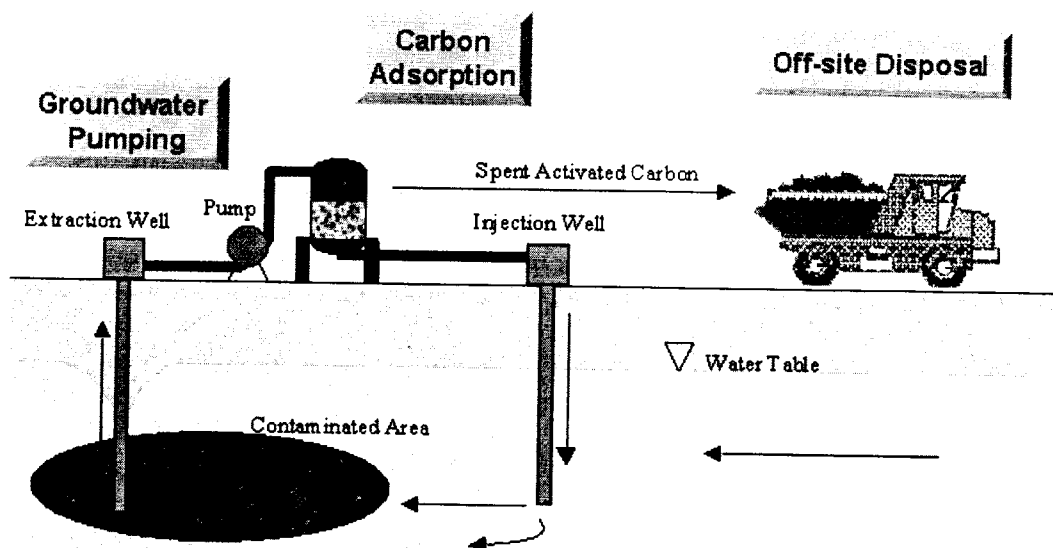


Figure 6: System diagram of a alternative common treatment train for VOCs (after van DEUREN et al. 1993).

System diagrams of a common treatment train for VOCs is illustrated in figures 5 and 6. In figure 5, a soil vapor extraction system is used to pull VOC vapor from the contaminated soil, thus favorizing the volatilization of the dissolved VOCs in contaminated groundwater plumes, too. An air sparging system delivers air below the water table to enhance bioremediation. After passing through a liquid/vapor separator, the VOC contaminated water and gas are pumped to a liquid phase granulated activated carbon dsorption system that removes VOCs in the water. The effluent is either discharged or pumped back as fluid recycling. Meanwhile, VOCs in the gas stream are completely destroyed through catalytic oxidation. Carbon dioxide and water vapor are discharged to the atmosphere as the final products of oxidation. In figure 6, a groundwater pumping system is used to pull contaminated water from the subsurface. This water is pumped to a liquid phase granulated activated carbon adsorption system removing VOCs in the water and the effluent is either discharged or re-injected back into the subsurface. Additionally, exhausted activated carbon taken off-site for either reactivation, regeneration, or disposal once the effluent (treated water) no longer meets the treatment objective.

4.2 Nonhalogenated and halogenated semivolatile organic compounds

Typical nonhalogenated SVOCs are nitrophenols, nitroanilines, anthracene, benzo(a)pyrene, chrysene, fluoranthene, phenanthrene, phthalates, fluorene, malathione, parathion, phenyl naphthalene, or pyrene. Halogenated SVOCs are e.g. the different chlorobenzenes, chlorophenols, or chlorophthalenes, further polychlorinated biphenyls (PCBs). Halogenated pesticides are e.g. aldrin, chlordane, 4,4'-DDT, dieldrin, endosulfans, heptochlor, malathiol, and toxaphene. The nature of the halogen bond and the halogen itself can significantly affect performance of a technology or require more intensive treatment than for nonhalogenated compounds. Generally, halogenated compounds are less amenable to bioremediation than nonhalogenated compounds.

Specific contaminant groups are the nonhalogenated and halogenated polycyclic aromatic hydrocarbons (PAHs), thousands of different pesticides, and polychlorinated biphenyls (PCBs), a class of chlorinated compounds that includes up to 209 variations or congeners with different physical and chemical characteristics. While occuring in groundwater, the pesticides have no bearing on applicable treatment technologies.

Sites where semivolatile organic compounds (SVOCs) may be found are the same as in the case of volatile organic compounds, and additionally wood preserving sites.

Subsurface contamination by SVOCs potentially exists in four phases such as in the case of the VOCs. While the degree of volatilization from SVOCs is much less than for VOCs, this process still occurs.

Common treatment technologies for SVOCs in soil include excavation with off-site disposal (landfilling of hazardous materials, especially hazardous wastes, is becoming increasingly difficult and expensive as a result of growing regulatory control), incineration, dehalogenation (as a typical treatment procedure for halogenated SVOCs using reagents which are added to soils contaminated with halogenated SVOCs; the dehalogenation process is achieved by either the replacement of the halogen molecules or the decomposition and partial volatilization of the contaminants) and biodegradation.

All types of biodegradation, both in-situ or ex-situ, can be considered to remediate soils: in-situ bioremediation, bioventing, composting, or landfarming. Biodegradation uses a process in which indigenous or inoculated microorganisms (e.g. fungi, bacteria, and other microbes) degrade (i.e. metabolize) organic contaminants found in soil. In the presence of sufficient oxygen (aerobic conditions), microorganisms will ultimately convert many organic contaminants to carbon dioxide, water, and microbial cell mass. In the absence of oxygen (anaerobic conditions), the contaminants will be ultimately metabolized to methane and carbon dioxide. The in-situ bioremediation of soil typically involves the percolation or injection of water mixed with nutrients. Ex-situ bioremediation typically uses tilling or continuously mixed slurries to apply oxygen and nutrients, and is performed in a prepared bed (liners and aeration) or reactor.

The most commonly used ex-situ treatment technologies for SVOCs in groundwater include carbon adsorption as in the case of VOCs and UV oxidation. UV oxidation is a destruction process that oxidizes organic and explosive constituents in contaminated waters by the addition of strong oxidizers and irradiation with intense UV light. The oxidation reactions are catalyzed by UV light, while ozone (O_3) and/or hydrogen peroxide (H_2O_2) are commonly used as oxidizing agents. The final products of oxidation are carbon dioxide, water, and salts.

In-situ treatment technologies are not widely used. Groundwater concentrations are usually not sufficiently high to support biological processes, however, biological process may be applicable to leachate.

A system diagram of common soil treatment trains for *nonhalogenated SVOCs* is illustrated in figure 7 resp. for *halogenated SVOCs* in figure 8. In figure 7, a thermally enhanced soil vapor extraction system is used to pull SVOC vapor from the contaminated soil. Electrodes are installed in the contamination zone to enhance the desorption of SVOCs from the contaminated soil. The traditional soil vapor extraction system then pulls out the SVOC contaminated soil gas. After initial thermally enhanced soil vapor extraction, in-situ bioremediation is used to carry out the second stage cleanup because it is more cost effective. Air and necessary nutrients are pumped into the contamination zone to enhance the intrinsic biodegradation. In figure 8, a treatment train for a common treatment of *halogenated SVOCs* is shown. Contaminated soil is excavated and transported to the treatment facility. A dehalogenation process is used to treat the contaminated soil first. In this process, soil is mixed with chemical reagents in a mixer and then passed through a reactor in which reactions between SVOCs and reagents take place. After dehalogenation, excess chemical reagents are separated from soil and recycled back to the mixer. Treated soil is finally cleaned by water in a soil washing process to remove contaminant residuals. Clean soil after dewatering is then ready for disposal.

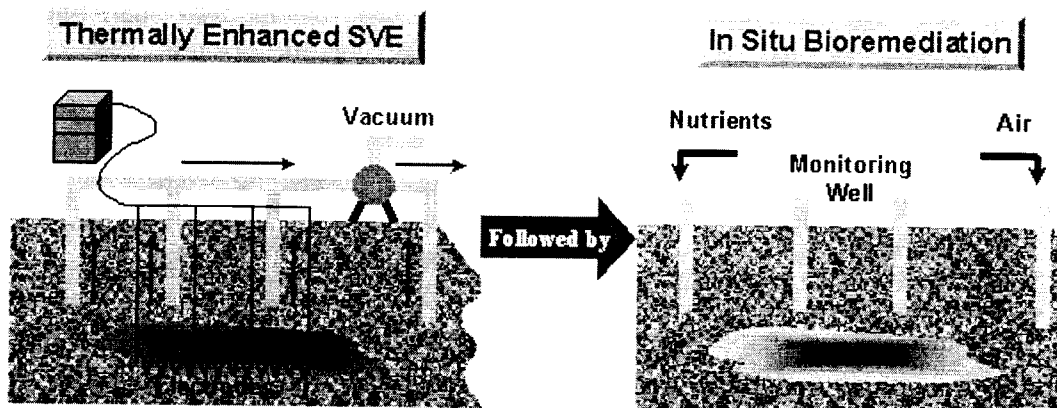


Figure 7: System diagram of an alternative common treatment train for nonhalogenated SVOCs (after van DEUREN et al. 1993).

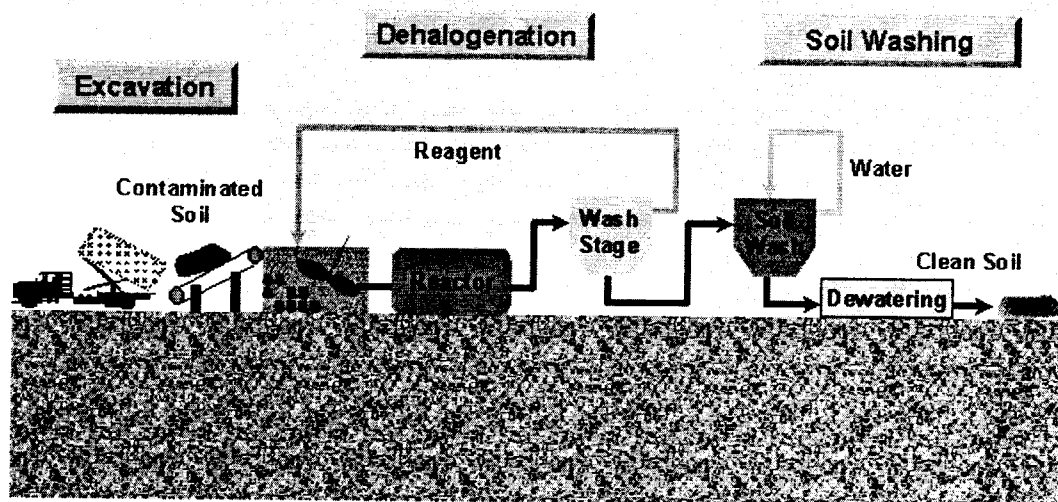


Figure 8: System diagram of an alternative common treatment train for halogenated SVOCs (after van DEUREN et al. 1993).

4.3 Fuels

Typical fuel contaminants include among other things the different trimethyl- and tetramethylbenzenes, the different di- and trimethylheptanes and -pentanes, methylbutenes, -pentenes, -heptanes, and -hexanes, benzenes, cyclohexanes and -pentanes, phenoles, pyrenes, toluenes, and the groups of n-butane, n-decane, n-heptane, n-octane etc.

Sites where fuel contaminants may be found include aircraft areas, burn pits, chemical disposal areas, contaminated marine sediments, disposal wells and leach fields, firefighting training areas, hangars/aircraft maintenance areas, landfills and burial pits, leaking storage tanks, solvent degreasing areas, surface impoundments, and vehicle maintenance areas.

Contamination by fuel contaminants, which are generally nonhalogenated, in the unsaturated zone exists in four phases such as the VOCs or SVOCs. Most fuel-derived contaminants are less dense than water and can be detected as floating pools (LNAPLs) on the water table. More volatile LNAPL compounds readily partition into the air phase. Dissolution of contaminants from residual saturation, or bulk liquid, into water may occur in either the unsaturated or saturated zones of the subsurface with the contamination then moving with the water.

Common treatment technologies for fuels in soil include biodegradation (using indigenous or inoculated microorganisms to degrade organic contaminants found in soil), incineration, soil vapor extraction, and low temperature thermal desorption (these physical separation processes are not designed to destroy organics; contaminated soils are heated to between 90 °C and 315 °C to volatilize water and organic contaminants, a carrier gas or vacuum system transports volatilized water and organics to the gas treatment system). Incineration is typically used when chlorinated SVOCs are also present with fuel, and not specified for fuel-only contaminated soil.

Technologies most commonly used to treat fuels in groundwater include air stripping, carbon adsorption, dual phase extraction, fluid/vapor extraction, and bioslurping. These are all ex-situ treatment technologies requiring groundwater extraction.

For *dual phase extraction*, undissolved liquid-phase organics are removed from subsurface formations, either by active methods (e.g. pumping) or a passive collection system. This process is used primarily in cases where a fuel hydrocarbon lens is floating on the water table. The free product is generally drawn up to the surface by a pumping system.

In *fluid/vapor extraction*, a high vacuum system is applied to simultaneously remove liquid and gas from low permeability or heterogeneous formations. The vacuum extraction well includes a screened section in the zone of contaminated soils and groundwater. It removes contaminants from above and below the water table. The system lowers the water table around the well, exposing more of the formation. Contaminants in the newly exposed vadose zone are then accessible to vapor extraction, which can remove contaminants more efficiently than pump-and-treat.

Bioslurping is the adaptation and application of vacuum-enhanced dewatering technologies to remediate hydrocarbon-contaminated sites. Bioslurping combines vacuum-assisted free-product recovery with bioventing to simultaneously recover free product and bioremediate vadose zone soils.

A system diagram of a common treatment train for fuel-contaminated groundwater is illustrated in figure 9. The fuel contaminated soil is first treated using a soil washing (soil flushing) process. Water is injected at the up stream side of the contaminated site. Detergents or other additives may be added to enhance the soil washing effect. Soil washing is difficult to achieve in silty and clayed soils, and the process has limited effectiveness when used as a remedial option only by itself. Contaminated groundwater resulting by soil washing is pulled out through extraction wells installed at the down stream side for further treatment.

An in-situ bioremediation process is used, following the initial soil washing, to complete the remediation. Nutrients and air may be pumped in to the site if necessary to enhance intrinsic bioremediation.

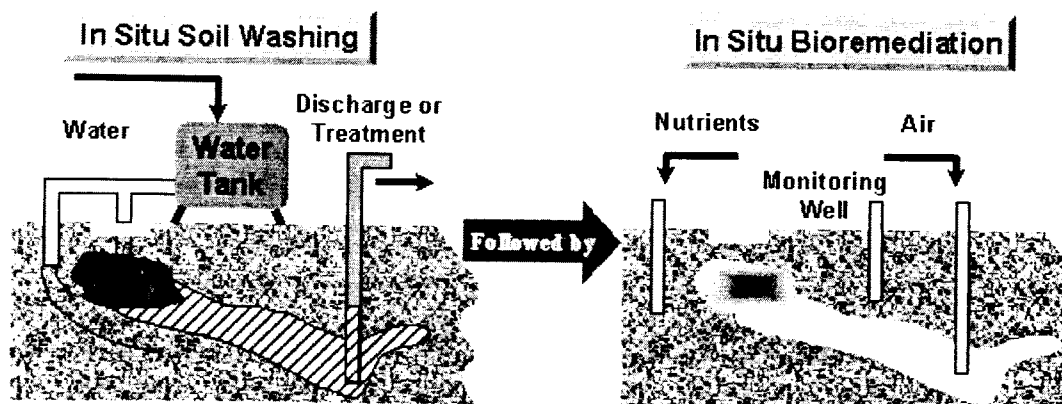


Figure 9: System diagram of common treatment train for fuels (after van DEUREN et al. 1993).

4.4 Inorganics

Typical inorganic contaminants include among other things the more or less toxic trace metals arsenic (arsenic is a metalloid, not a true metal), cadmium, chromium, cobalt copper, lead, mercury, nickel and zinc, furthermore asbestos, fluorine, and cyanide.

Sites where inorganic contaminants may be found include artillery and small arms impact areas, battery disposal area, burn pits, chemical disposal areas, disposal wells and leach fields, electroplating/metal finishing shops, firefighting training areas, landfills and burial pits, leaking collection and system sanitary lines, leaking storage tanks, radioactive and mixed waste disposal areas, oxidation ponds/lagoons, paint stripping and spray booth areas, sand blasting areas, surface impoundments, and vehicle maintenance areas.

Metals may be found in the elemental form, but more often they are found as salts mixed in the soil. Unlike the hazardous organic constituents, metals cannot be degraded or readily detoxified. The presence of metals among in contaminated soils can pose a long-term environmental hazard. The fate of the metal depends on its physical and chemical properties, and the soil. Significant downward transportation of metals from the soil surface occurs when the metal retention capacity of the soil is overloaded, or when metals are solubilized (e.g. by low pH). As the concentration of metals exceeds the ability of the soil to retain them, the metals will travel downward with the leaching waters. Surface transport through dust and erosion of soils are common transport mechanisms.

The most commonly used treatment technologies for inorganics in soil include solidification/stabilization, partially vitrification, excavation and off-site disposal, and acid extraction.

Solidification processes produce monolithic blocks of contaminated soil with high structural integrity. The contaminants do not necessarily interact chemically with the solidification reagents (typically cement/ash), but are mechanically locked within the solidified matrix. Stabilization methods usually involve the addition of chemical binders, such as cement, silicates, or pozzolans, which limit the solubility or mobility of waste constituents even though the physical handling characteristics of the waste may not be changed or improved. Solidification/stabilization of radionuclides can be conducted either in-situ or ex-situ.

Vitrification, or molten glass, processes are solidification methods that employ heat up to 1,200 °C to melt and convert waste materials into glass or other glass and crystalline products. The high temperatures destroy any organic constituents with very few by-products. Materials are actually incorporated into the glass structure which is, generally, a relatively strong, durable material that is resistant to leaching.

Acid extraction uses an acid, such as hydrochloric acid, to extract heavy metal contaminants from soils. In this process, soils are first screened to remove coarse solids. Acid is then introduced into the soil in the extraction unit. The residence time in the unit varies depending on the soil type, contaminants, and contaminant concentrations, but generally ranges between 10 and 40 minutes. The soil-extractant mixture is continuously pumped out of the mixing tank, and the soil and extractant are separated using hydrocyclones.

Precipitation, filtration, and ion exchange are widely used ex-situ treatment technologies for inorganics in groundwater. In-situ treatment technologies are used less frequently.

The combination of precipitation/flocculation and sedimentation is a well-established technology for the removal of metals from groundwater. This technology pumps groundwater

through extraction wells and then treats it to precipitate lead and other heavy metals. Typical removal of metals employs precipitation with hydroxides, carbonates, or sulfides.

Filtration isolates solid particles by running a fluid stream through a porous medium. The driving force is either gravity or a pressure differential across the filtration medium. Pressure differentiated filtration techniques include separation by centrifugal force, vacuum, or positive pressure. The chemicals are not destroyed; they are merely concentrated, making reclamation possible.

All metallic elements present as soluble species, either anionic or cationic, can be removed by ion exchange, whereby the toxic ions are removed from the aqueous phase in an exchange with relatively innocuous ions (e.g. NaCl) held by the ion exchange material. Modern ion exchange resins consist of synthetic organic materials containing ionic functional groups to which exchangeable ions are attached. Other types of ion exchange materials include clays, zeolites, and peat derivatives. The exchange reaction is reversible and concentration-dependent; the exchange resins are regenerable for reuse.

A system diagram of a common treatment train for inorganics is illustrated in figure 10. Metal contaminated soil is treated using the combination of electrokinetics and phytoremediation. Electrokinetics is used to remove metals from deep soil and groundwater. A low density direct current is applied to mobilize charged species, causing ions and water to move toward the electrodes. Metal ions move toward the cathode, and anions move toward anode. Removal of metal contaminants at the electrode may be accomplished by electroplating at the electrode, precipitation or co-precipitation at the electrode, pumping of water near the electrode. Metals in the top soil can be removed by phytoremediation. Metal ions are picked up by plant roots and accumulated into plant shoots and leaves.

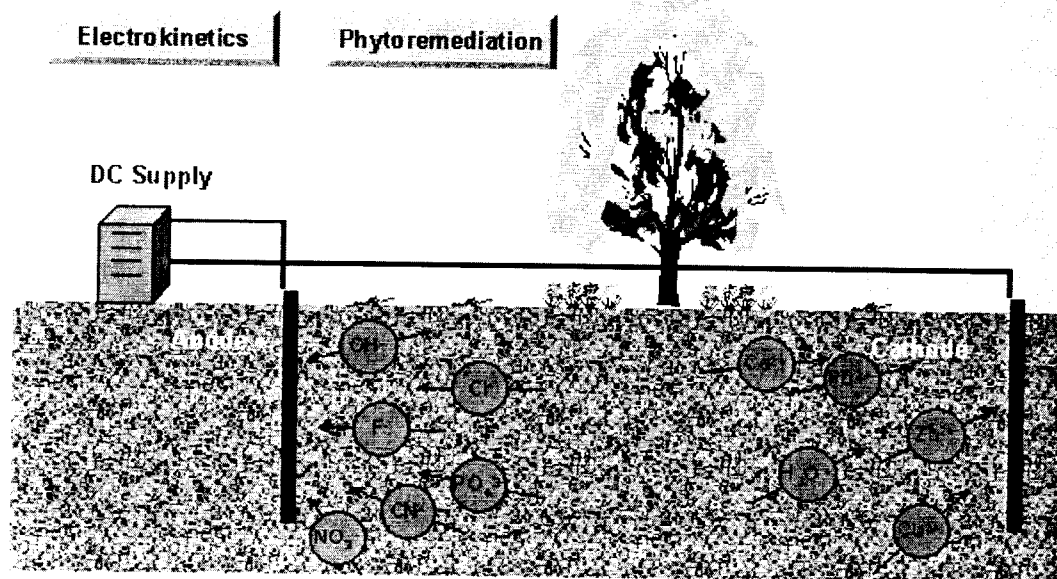


Figure 10: System diagram of common treatment train for inorganics (after van DEUREN et al. 1993).

4.5 Radionuclides

Radionuclides of interest are among others things cesium-134, -137, cobalt-60, plutonium-238, -239, -241, strontium-89, -90, and uranium-234, -235, -238. Radionuclides should be considered to have properties similar to those of other heavy metals. This imply that the

majority of sites requiring remediation of radioactively contaminated materials are contaminated with radionuclides that have similar properties. Like metals, the contaminants of concern are typically nonvolatile and less soluble in water than some other contaminants. However, the solubility and volatility of individual radionuclides will vary and should be evaluated for each wastestream being remediated.

Sites where radionuclide contaminants may be found are mainly radioactive and mixed waste disposal areas.

Implementation of remediation technologies should consider the potential for radiological exposure to workers (internal and external) and the technologies themselves. The degree of hazard is based on the radionuclide(s) present and the type and energy of radiation emitted (i.e. alpha particles, beta particles, gamma radiation, and neutron radiation).

Unlike organic contaminants (and similar to metals), radionuclides cannot be destroyed or degraded; therefore, remediation technologies applicable to radionuclides involve separation, concentration/volume reduction, and/or immobilization. The most commonly used treatment technology for radionuclides in soil is solidification/stabilization, a special, innovative form is vitrification.

Precipitation, filtration, and ion exchange are widely used treatment technologies for radionuclides in groundwater.

A system diagram of a common treatment train for radionuclides is illustrated in figure 11. Radionuclide contaminated soil is first excavated from the contamination soil and transported to a vitrification-site. During vitrification, the contaminated soil is molten at extremely high temperatures. Radionuclides are incorporated into the molten glass structure, which is a strong durable material resistant to leaching.

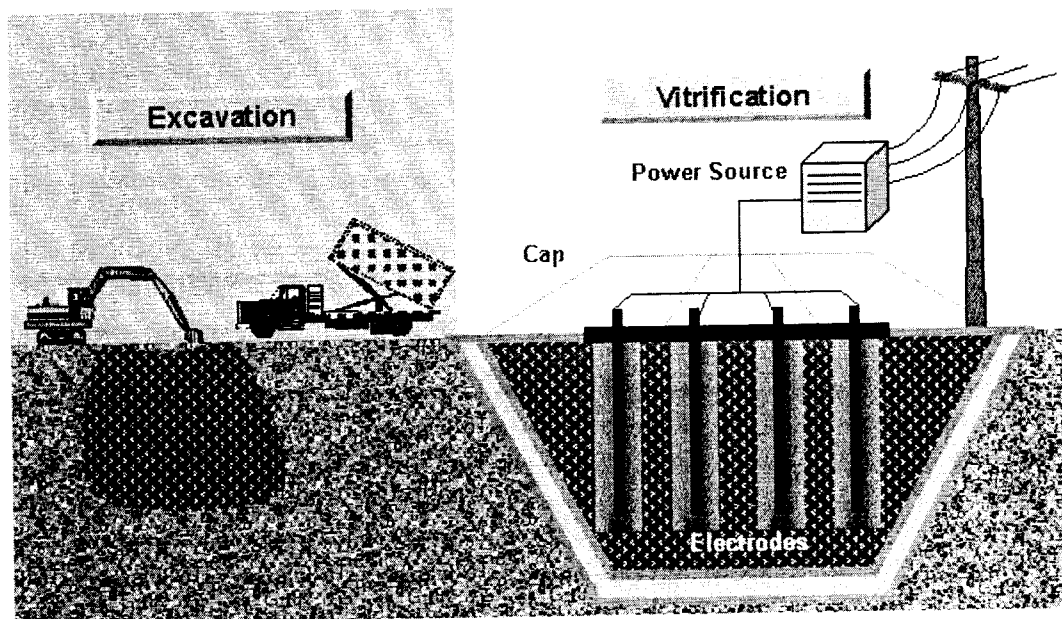


Figure 11: System diagram of common treatment train for inorganics (after van DEUREN et al. 1993).

4.5 Explosives

Typical explosive contaminants encountered at many sites include under other things TNT (2,4,6-trinitrotoluene), nitroaromatics, picrates, TNB (trinitrobenzenes), TNB (trinitrobenzenes), DNB (dinitrobenzenes), AP (ammonium perchlorate), nitroglycerine, and nitrocellulose. TNT (NO_2 groups are bonded to the aromatic ring) is the most common contaminant, occur-

ring in approximately 80 % of soil samples from US army sites found to be contaminated with explosives.

Sites where explosive contaminants may be found include artillery/impact areas, disposal wells, leach fields, landfills, burial pits, and TNT washout lagoons.

The term „explosives“ commonly is used to refer to propellants, explosives, and pyrotechnics, which technically fall into the more general category of energetic materials. These materials are susceptible to initiation, or self-sustained energy release, when present in sufficient quantities and exposed to stimuli such as heat, shock, friction, chemical incompatibility, or electrostatic discharge. Explosives manufacturing plants to produce various forms of explosives used in military ordnance result in the production of organic wastewaters that contain both explosive residues and other organic chemicals. Past waste handling practices at such plants commonly included the use of unlined lagoons or pits for containing process waters. As a result of these practices, some explosive residues may leach through the soil and contaminate groundwater.

Work, sampling, and health and safety plans for explosives waste sites should incorporate safety provisions that normally would not be included in work and sampling plans for other sites.

Biological, thermal, and other (such as reuse/recycle) treatment technologies are available to treat explosives-contaminated soils.

Bioremediation is most effective for dilute solutions of explosives and propellants. TNT in the crystalline form is difficult to treat biologically. Six biological treatments for explosives-contaminated soils are developed or implemented: aqueous-phase bioreactor treatment; composting, land farming, phytoremediation, and white rot fungus treatment, which are solid-phase treatments, and in-situ biological treatment.

Thermal treatment technologies can be divided in three categories. Hot gas decontamination is a technology still in the pilot-scale of development that can be used for decontamination of explosives-contaminated masonry or metallic structures. The method involves sealing and insulating the structures, heating with hot gas stream to 260 °C for a prescribed period of time, volatilizing the explosive contaminants, and destroying them in an afterburner. *Incineration* processes can be used to treat explosive-contaminated soils. Open burn/open detonation operations are conducted to destroy unserviceable, unstable, or unusable munitions and explosive materials. Explosives or munitions are destroyed by self-sustained combustion resp. by a detonation initiated by a disposal charge.

Other treatment technologies include reuse/recycle, solvent extraction, soil washing (currently being developed in Stadtallendorf, Germany; the process can reduce levels of explosive contamination in soils to low ppm levels), solar detoxification, and photocatalytic processes (using a semiconductor catalyst such as titanium dioxide in conjunction with near UV light to generate strongly oxidizing and reducing species).

Based upon process wastewater treatment experience, potentially applicable treatment technologies for groundwater are available. However, the similarities and differences between process wastewaters and explosives-contaminated groundwater should be considered before transferring technologies from one application to another. Granular-activated carbon adsorption is commonly used for explosives-contaminated groundwater treatment, including groundwater contaminated from disposal of process waters from the manufacture and demilitarization of munitions. Ultraviolet (UV) oxidation can be an effective treatment for explosives-contaminated groundwater and, unlike carbon treatment, actually destroys target compounds rather than just transferring them to a more easily disposable medium.

A system diagram of a common treatment train for explosives is illustrated in figure 12. Explosive contaminated soil is first excavated from the site and transported to a windrow composting site. During windrow composting, contaminated soil is placed in a pile under a protective shelter and mixed with readily degradable carbon sources by a mechanical mixing vehicle.

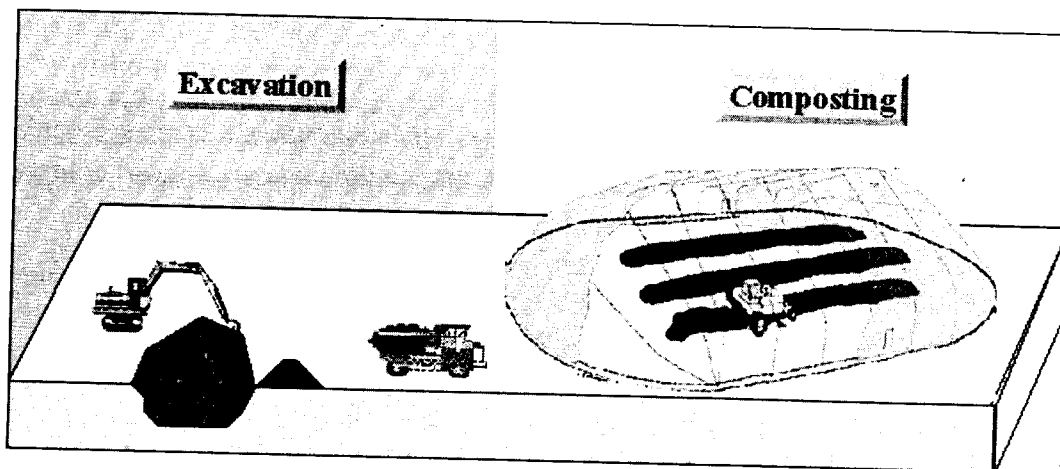


Figure 12: System diagram of common treatment train for explosives (after van DEUREN et al. 1993).

5. Overview of some groundwater remediation and treatment technologies with more details

Groundwater remediation strategies may be broadly classified in three groups. The first approach means protection measures against a danger. Characteristic for this conception is the hydraulical or geotechnical diversion of contamination plume; the pollutants remain in the groundwater, but they do not pass in water supply wells, for instance. The second approach lays emphasis on the containment of contaminants. A typical example is the encapsulation of abandoned waste deposits; the pollutants are not removed from the underground, they were isolated from the environment. The third approach is the reduction or total elimination of pollutants, that means the clean-up of groundwater in a narrow sense. This third approach can be differentiated in two sub-groups. One sub-group requires displacement of the contamination to another location for treatment. The most commonly applied members of this on-site (without transport) or off-site-technology (with transport to an external cleanup device) include groundwater pump-and-treat systems, soil vapor extraction systems, and free product recovery systems. The second sub-group may be called in-situ technologies with the two most common members: soil bioremediation and groundwater bioremediation. Bioremediation is the process by which the growth and activity of naturally occurring microorganisms are stimulated, and thus, microorganisms degrade through their metabolic processes the compounds of interest.

With view of applied technologies for controlling groundwater contamination generally one can differ three basic categories or a combination thereof: 1) pump-and-treat systems, which pump the groundwater for in-situ or on-site/off-site treatment (mostly chemical or biological), 2) source and/or plume containment through groundwater pumping, groundwater injection, and/or the use of subsurface barrier walls, and 3) passive treatment using chemically or biologically reactive barrier walls.

Successful aquifer clean-up is basing on two basic activities. One precondition is the removal of any remaining free or residual organic products. The more liquid pollutants can be removed, the more effective the groundwater remediation will generally be. When mobile or resi-

dual liquid phase is present, remediation is likely to be very difficult and may require pumping for hundred of years. A second precondition is the removal of contaminants remaining in the vadose zone. If this latter activity is not carried out, water infiltration through the unsaturated zone will continue to leach the contaminants into the groundwater. Therefore, the prior recovering of free products (DNAPLs or LNAPLs) is a must (4). In the case of volatile materials present in the unsaturated and/or in the saturated zone, vapor stripping (soil venting) by inducing or forcing an air movement through the soil is recommended as additional clean up measure (5).

The soil is only considered in connection with groundwater problems. No subject of this paper is also the simple excavation of contaminated soil without treatment because this procedure is only moving the problem around.

- Pump-and-treat systems

Pumping combined with the following treatment of the contaminated groundwater from the subsurface through the use of extraction wells is the most common remedial technique, called „pump-and-treat". The goal of the hydraulic control of the contaminant plume is to prevent further contamination outside the source area. Pump-and-treat can be accomplished by constructing wells or by implementing a trench system perpendicular to the direction of groundwater flow. Trench systems are used especially at sites with shallow groundwater (depth to groundwater table < 5 m) and aquifers, which have a low permeability.

Once at the surface, groundwater can be treated in a variety of ways.

- Air stripping

Air stripping involves the mass transfer of volatile contaminants from water to air. For groundwater remediation, this process is typically conducted in a packed tower or an aeration tank.

The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated water over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect decontaminated water (fig. 13). Auxiliary equipment that can be added to the basic air stripper includes an air heater to improve removal efficiencies, and air emission control and treatment systems, such as activated carbon units, catalytic oxidizers, or thermal oxidizers. Packed tower air strippers are installed either as permanent installations on concrete pads or on a skid or a trailer.

Aeration tanks strip volatile compounds by bubbling air into a tank through which contaminated water flows. A forced air blower and a distribution manifold are designed to ensure air-water contact without the need for any packing materials. The baffles and multiple units ensure adequate residence time for stripping to occur. Aeration tanks are typically sold as continuously operated skid-mounted units. The main advantage offered by aeration tanks is a considerably lower profile (less than 2 meters high) than packed column towers (5 to 12 meters high) where the height may be a problem. The discharge air from aeration tanks can be treated using the same technology as for packed tower air discharge treatment.

Air stripping is used to separate volatile organic compounds (VOCs) from water. Henry's law constant is used to determine whether air stripping will be effective. Generally, organic compounds with constants greater than 0.01 atmospheres (m^3/mol) are considered amenable to stripping. Some compounds that have been successfully separated from water using air stripping include BTEX, and most of the the halogenated aliphatic hydrocarbons.

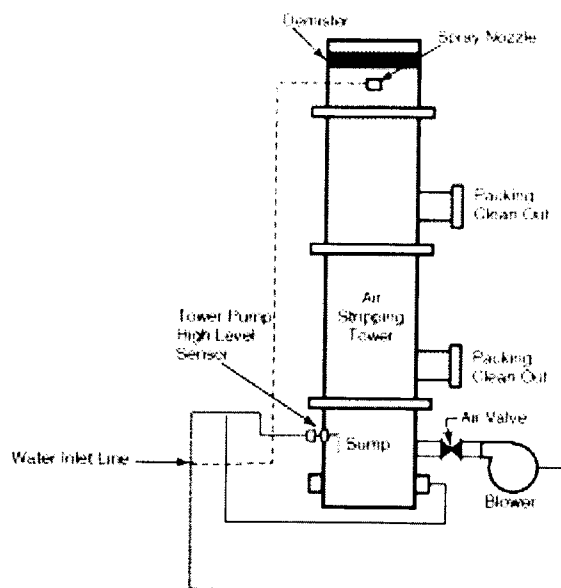


Figure 13: Typical air stripping system – packed tower (after van DEUREN et al. 1993).

- Granular activated carbon adsorption (liquid phase)

Adsorption by activated carbon has a long history of use in treating municipal, industrial, and hazardous wastewaters. Granular activated carbon adsorption is a full-scale technology in which groundwater is pumped through a series of vessels containing activated carbon to which dissolved contaminants adsorb (fig. 14). When the concentration of contaminants in the effluent from the bed exceeds a certain level, the carbon can be regenerated in place, removed and regenerated at an off-site facility, or removed and disposed of.

The two most common reactor configurations for carbon adsorption systems are the fixed bed and the pulsed or moving bed. The fixed-bed configuration is the most widely used for adsorption from liquids. Suspended solids in a liquid stream may accumulate in the column, causing an increase in pressure drop. When the pressure drop becomes too high, the accumulated solids must be removed, for example, by backwashing. The solids removal process necessitates adsorber downtime and may result in carbon loss and disruption of the mass transfer zone. Pretreatment for removal of solids from streams to be treated is, therefore, an important design consideration.

Carbon can be used in conjunction with steam reforming. Steam reforming is a technology designed to destroy halogenated solvents adsorbed on activated carbon by reaction with superheated steam in a commercial reactor.

The target contaminant groups for carbon adsorption are VOCs and explosives. Granular activated carbon adsorption is effective for removing contaminants at low concentrations (less than 10 mg/l) from water at nearly any flow rate, and for removing higher concentrations of contaminants from water at low flow rates (typically 2 to 4 liters per minute). Carbon adsorption systems can be deployed rapidly, and contaminant removal efficiencies are high. Logistic and economic disadvantages arise from the need to transport and decontaminate spent carbon.

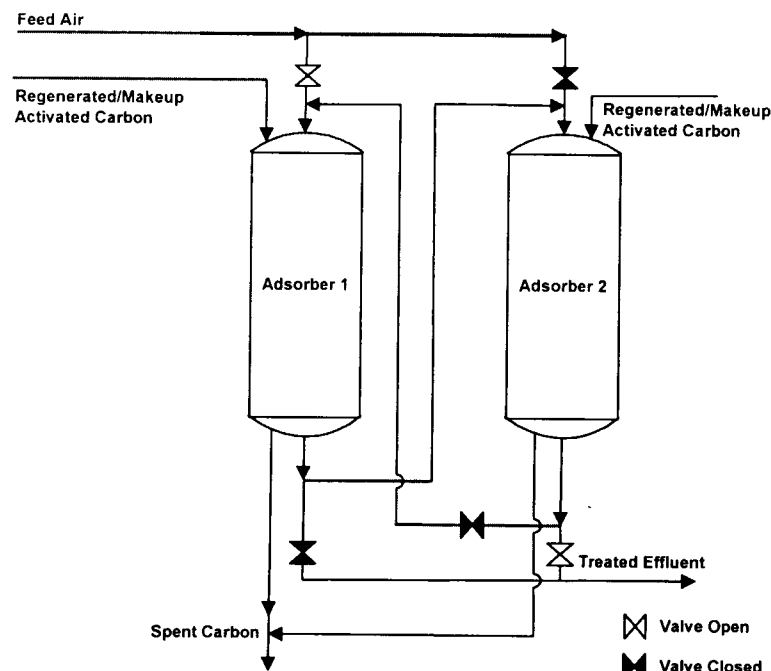


Figure 14: Typical activated carbon system (after van DEUREN et al. 1993).

- Bioreactors

Onsite/off-site technologies include a wide variety of bioreactors, ranging from small (1-5 m³) portable units to large plants built specifically for polluted site. Bioreactors are being used either for reducing nitrate in groundwater or for removing hydrocarbons from abstracted groundwater (fig. 15).

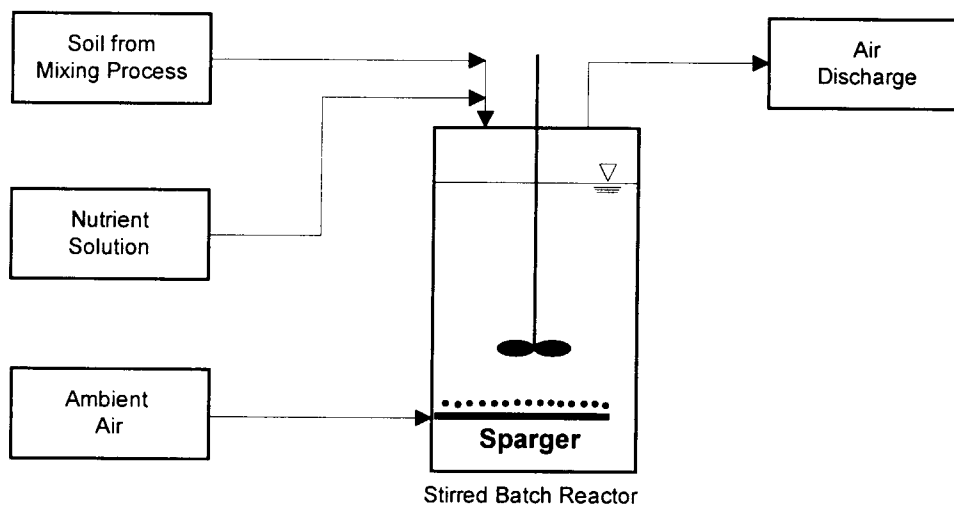


Figure 15: Sketch of a typical bioreactor process (after van DEUREN et al. 1993).

The nitrate reducing bioreactor approach involves adding a carbon source (methanol, butan gas, etc.) which leads to the consumption of dissolved oxygen. When water becomes anoxic and both organic carbon and nitrate are abundant, some bacteria switch from oxygen-based respiration to nitrate-based respiration. In the latter mode of respiration, the carbon is converted to microbial biomass and CO₂, and nitrate is converted to a gaseous nitrogen compound (usually N₂, but also N₂O or NO gas). Methanol or butan are probably more economic as a carbon source than glucose, and furthermore they result in a more stable process. Alternatively, any high BOD processing waste could work (BOD = biological oxygen demand). Water

with residual organic carbon returned onto the heap could result in sliming and plugging of channels. This would be avoided by carefully controlling the dosing of organic carbon.

Bioreactors removing organic compounds from contaminated groundwater are biochemical processing systems designed to degrade contaminants such as primarily nonhalogenated VOCs and SVOCs, including gasoline, diesel fuel, kerosene, and heavy fuels in extracted groundwater through attached or suspended biological systems. In suspended growth systems, such as activated sludge, fluidized beds, or sequencing batch reactors, contaminated groundwater is circulated in an aeration basin where a microbial population aerobically degrades organic matter and produces CO_2 , H_2O , and new cells. The cells form a sludge, which is settled out in a clarifier, and is either recycled to the aeration basin or disposed of. In attached biofilm systems, such as upflow fixed film bioreactors, rotating biological contactors, and trickling filters, microorganisms are established on a support matrix to aerobically degrade water contaminants. One promising methodology includes the use of adsorption media, such as activated carbon, which adsorbs contaminants and slowly releases them to the microorganisms for degradation. The microbial population may be derived either from the contaminant source or from an inoculum of organisms specific to a contaminant.

Experience with pump-and-treat has proven that the effectiveness of the technology is generally limited to removal of the highest contaminant concentrations from the groundwater at or near the original contaminant source area. This is mainly due to a combination of the following factors:

- In most aquifers, the pattern of water flow is not uniform. If the hydraulic conductivity is too low or the hydrogeological conditions are very complex and heterogeneous, then pumping may not be a feasible alternative for clean-up. Because a significant portion of contamination is typically present in the adsorbed and residual phases pollutants stored in low permeable strata tend to cause a concentration tailing in the pumped groundwater which will enlarge the decontamination time significantly.
- Contaminants that have been in the ground for an extended period of time diffused (i.e. moved) into less permeable areas of the aquifer (so-called matrix diffusion). Since the majority of water pumped comes from the most permeable zones of the aquifer, clean-up times are significantly extended under these conditions.
- The ability of pump-and-treat systems is severely limited by the solubility of the contaminants in water. Estimates indicate that it could take more than several 100 years to remove tetrachloroethene by using water as the carrier. More soluble compounds such as salts may take less time.
- Pump-and-treat technology is effective in reducing the mass of organic compounds in contaminated groundwater. However, it is not capable of reducing contaminant concentrations to the lower part of the $\mu\text{g/l}$ range respectively to drinking water standards, which is often a requirement, unless we are willing to wait for decades or centuries operation.

At many sites, the natural conditions of an aquifer work together to impede remediation through the use of pump-and-treat systems alone. Therefore, the prevailing opinion is that a more appropriate use for pump-and-treat technology is that of plume containment (see later).

In contrast to that, nowadays in-situ biotreatment is a part of pump-and-treat systems at many contaminated sites. In-situ biological treatment uses microorganisms (mostly bacteria) to remove organic compounds in groundwater through metabolic processes. The most aerobically biodegradable compounds in the subsurface are petroleum hydrocarbons such as gasoline or crude oil, fuel oil, and aviation gas. A typical example for anaerobic degradation are the halogenated DNAPLs, their cometabolic degradation by microbiology is a very slow process.

Bioremediation involves establishing the conditions in contaminated environment so that appropriate microorganisms flourish and carry out the metabolic activities to destruct partially or completely the contaminants. Using preferably indigenous microflora is called bioremediation. Biostimulation means encouraging biodegradation activity of indigenous (native) microflora and supplementing nutrients and other favourable conditions. During bioremediation microorganisms may use the contaminants as carbon or energy source.

Many organic compounds in the subsurface are resistant to degradation as for instance the polycyclic aromatic hydrocarbons. Furthermore, the removal of any free product at the site is the precondition for success as only the compounds dissolved in water or occurring in residual saturation are biodegradable, not the liquid phase. Heavy metals and toxic concentrations of organics may inhibit microbial activity.

Prior to the initiation of a bioremediation activity, it is important to conduct a feasibility study. Laboratory studies (for instance batch culture techniques) have to be performed to support the successful implementation of the bioremediation technology at the field-scale.

Enhanced bioremediation is essentially an engineering delivery of nutrients as phosphorus and ammonium salts, adding terminal electron acceptor (in Germany favourably NO_3 , in the United States of America commonly H_2O_2), adjusting moisture conditions or raising the temperature etc. to promote the growth of particular organisms. The basic concept is to provide critical environmental requirements which may be adverse in particular site. The entire area then acts like a bioreactor.

One or several collector wells abstract the contaminated groundwater. After pre-treatment on surface (in a bioreactor, etc.) and supplemented with nutrients and eventually with useful microorganisms the abstracted groundwater is re-introduced by injection into the subsurface through wells or trenches upgradient of pumping well(s). Thus, a water circulation is installed which enables a high groundwater flow velocity and flux aiding to flush the contamination towards the extraction wells (fig. 16).

A system for injection of nutrients into the aquifer and circulation through the contaminated portion of the underground must be properly managed. Nitrate or nutrients added must be hydraulically contained within the treatment zone to prevent further contamination of untargeted areas. Metabolites of partial degradation of organic compounds may impart objectionable tastes or odours. Therefore, hydraulic control or the limitation of the movement of the plume must always be accomplished before any other remedial activity can succeed. The groundwater flow field should be prognosticated by a prior application of a numerical groundwater model.

In addition to treatment of the saturated zone by pumping nutrients and electron acceptors in the groundwater, organics held in the unsaturated and capillary zones can sometimes be degraded when an infiltration gallery or soil flushing is used or the nutrients are trickled from the surface.

Sometimes one or several additional protecting wells are installed in which water of drinking water quality is injected or infiltrated into the underground creating a water divide between the nitrified water in the depression cone around the abstraction well(s) and the not influenced groundwater.

Innovative modifications include the use of detergents and chemical enhancements to facilitate the flushing effect. These techniques are still in the experimental phase and are not fully understood.

In-situ bioremediation provides a potentially significant benefit for volatile organic compounds and other contaminants that are held up in adsorptive soils or less permeable sediments, and clays that act as sinks. The main limitation of this technology when compared with baseline methods is the difficulty in designing and implementing an effective subsurface treat-

ment system for highly heterogeneous media. Several key technical issues have prevented widespread use of bioremediation for organic and inorganic subsurface contaminants. These are adequate nutrient delivery systems, effective mixing for contacting micro-organisms, nutrients, contaminants, control of biofouling or excessive microbial growth, and adequate tools for designing, predicting, and monitoring the performance of in-situ technologies in heterogeneous subsurface environments.

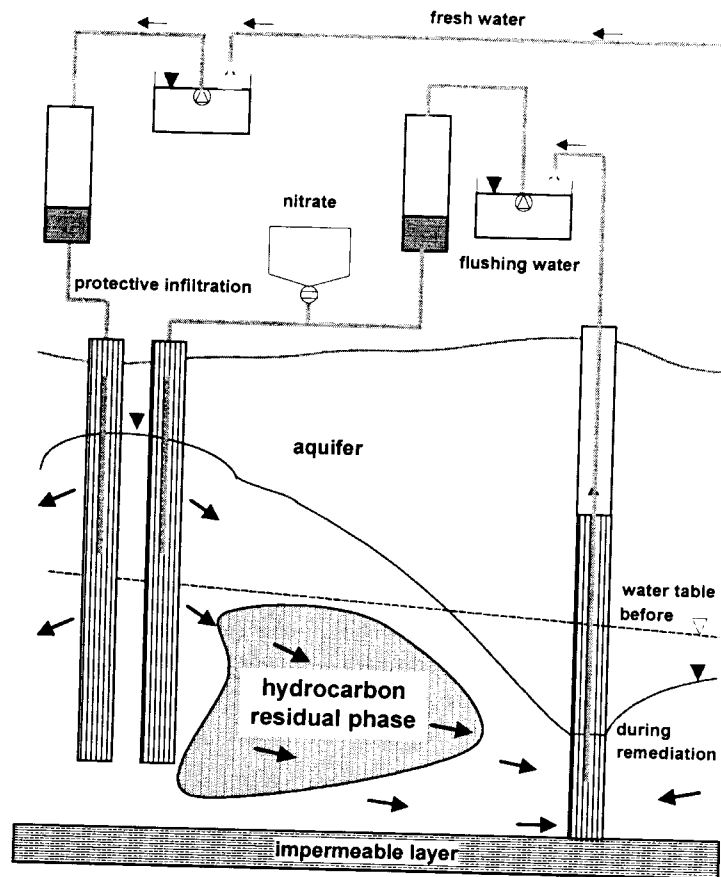


Figure 16: Sketch of in-situ groundwater remediation with flushing circuit in a porous aquifer.

The physical, chemical, and/or biological properties of each contaminant are evaluated to determine the appropriate treatment technology to meet effluent criteria. Effluent criteria depend on how the water is to be disposed of. Disposal options include storage in tanks, discharge to a wastewater treatment facility, and reinjection through wells, trenches, leachfields, or recharge basins.

- Containment systems

Where it is not be feasible or technically possible to fully remediate an aquifer - this is especially true at sites where the source of contamination cannot be located and removed - hydraulic or physical/geotechnical containment may be the most viable long term solution. This can be accomplished by groundwater pumping, groundwater injection, or installation of a cut-off wall. As the contaminants are not removed from the protected media resp. are not eliminated generally, this technology is not to be considered as remediation procedure in its narrow sense.

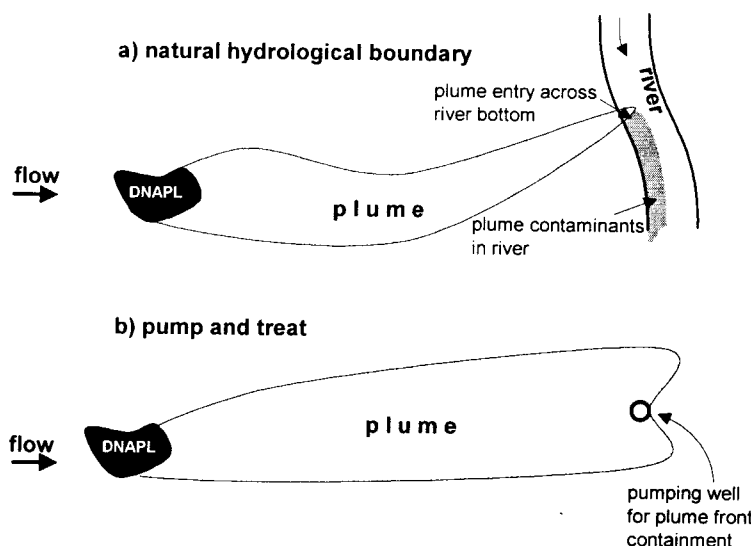


Figure 17: Plume containment: a) river as natural boundary, and b) pump-and-treat captures the front of plume.

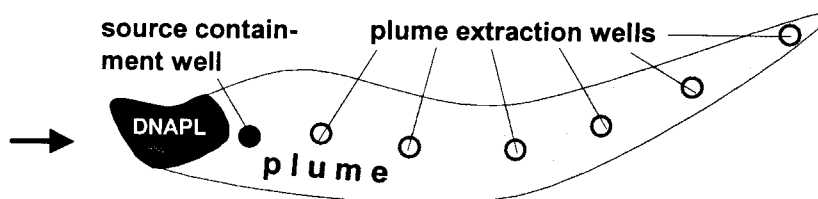


Figure 18: Remediation of a source zone and its plume by pump-and-treat - containment well at the source zone and multiple wells in the plume.

Plume containment through groundwater pumping is achieved by installing one or more wells, or by using existing wells to pump only enough water to capture the plume (fig. 17 and 18). The number of the wells or trenches, their locations and spacing, and the required pumping rates are the most important design parameters. Careful monitoring is the key to understand how the system "aquifer" will respond over time.

The capture zone of the well(s) depends on the pumping rate and the aquifer conditions. Ideally, the capture zone should be somewhat larger than the plume to be cleaned up; wells can be added until sufficient pumping capacity is provided to create a useful capture zone. However, with more wells, some contaminants may pass between the wells, and well spacing becomes an important parameter as well as pumping rate. The greater the pumping rate, the larger the capture zone, and the closer the wells are placed, the better the chance of complete plume capture.

The pumped water is generally treated prior to disposal, or reinjected up-gradient to recirculate through the aquifer. Injection of water can also be performed downgradient to create an artificial ridge of higher hydraulic head, which forces the plume to change direction. This may be a desirable technique for use during initial response or when a short term groundwater diversion is needed.

Physical barriers made of low permeability materials are also widely used for containment of a contaminant source or groundwater plume (fig. 19). These geotechnical containment systems are most commonly used in conjunction with pump-and-treat or other remediation technologies or as interim measures while remediation alternatives are considered.

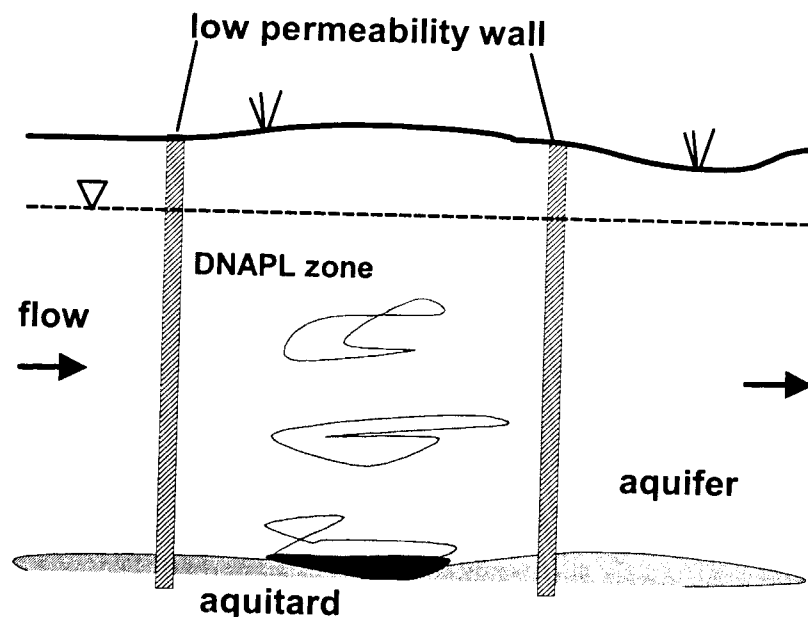


Figure 19: Cutoff wall keyed enclosure.

One can differ between surface sealing, vertical sealing and sealing of the bottom of a pollution source. Surface sealing will reduce the potential for contaminant transport by reducing the downward movement of water through the soil. A typical containment installation is the placement of a vertical barrier to prevent lateral migration of pollutants. Sheet piling, grout curtains and slurry walls are the most common forms of low permeability barriers. Sheet piling involves driving lengths of steel that connect together into the ground to form a thin and impermeable barrier to groundwater flow. When the barrier is to be left in place for extended periods of time, the steel is generally coated to protect it from corrosion. Grouting is the process of injecting a liquid, slurry, or emulsion under pressure into the soil. The fluid moves away from the point of injection to occupy void or open spaces in the soil. After a certain time period elapses, the injected fluid solidifies creating a low permeability barrier. Grouts can be classified as particulate or chemical, depending on the materials used. Particulate grouts consist of water and particulate materials which solidify in the subsurface, while chemical grouts consists of two or more liquids which gel as they come into contact with each other.

The most common slurry walls encapsulate an area to prevent groundwater pollution or to restrict the movement of a contaminated groundwater plume. The technology involves digging a trench around an area and backfilling the excavation with an impermeable material. Slurry walls are generally constructed with a cement-bentonite mix or a soil-bentonite mix.

It must strongly stressed that the desired sealing effect can only be reached, when the vertical barrier is anchored to an aquiclude, at least to an aquitard with a low permeability. Effective containment designs will include consideration of a natural barrier (unfractured unweathered rock or thick natural clay deposits) at the bottom of the containment wall. The reason is, that the artificial sealing by means of vertical injection wells in combination with chemicals (silicone, epoxy resins) or soil cement requires a high number of wells and that the integrity of the bottom seal is marginal to poor. An alternative may be sealing a site with mining technologies, but it is too expensive. A newly patented technology is using a rotating horizontally guided drilling tool which is powered by high pressure water and a drilling suspension. The lateral overlapping injections create a three dimensional barrier.

Deep barriers mean high costs and a major risk still remains. The use of these methods at hazardous waste sites can very often result in serious problems of leakage through and around the barriers. Therefore hydraulic controls are generally preferred for most cases.

Geotechnical barriers can be used to divert the groundwater flow, too. Combinations with hydraulical containment technologies are possible and often useful.

- Reactive barrier walls

The technology of permeable reactive barriers in the kind of passive barriers, passive treatment walls, treatment walls, or trenches is considered to be in its infancy, with limited field scale trials reported. An in-ground trench is backfilled with reactive media to provide passive treatment of contaminated groundwater passing through the trench. Treatment wall is placed at strategic location to intercept the contaminant plume and backfilled with media such as zero-valent iron, microorganisms, zeolite, activated carbon, peat, bentonite, limestone, saw dust, or other.

Physical barrier walls (i.e. sheet piling, grout curtains, or slurry walls) can be incorporated to channel groundwater through the reactive treatment wall. This combination of physical barrier walls with passive treatment walls is often referred to as a funnel-and-gate system. An example of a typical funnel-and-gate system can be found in figure 20.

The treatment processes which occur within the treatment wall are typically contaminant degradation, sorption or precipitation. The technology is applicable to a wide range of organic and inorganic contaminants, therefore the choice of media for treatment wall is based on specific contaminants. For chlorinated ethenes (PCE and TCE) the products are mostly fully dechlorinated (e.g. little vinyl chloride was observed), although some chlorinated alkanes produce partial dechlorination products that can be problematic. The zero-valent metal is the bulk reducing agent in these systems. However, corrosion of iron metal yields ferrous iron and hydrogen, both of which are possible reducing agents relative to contaminants.

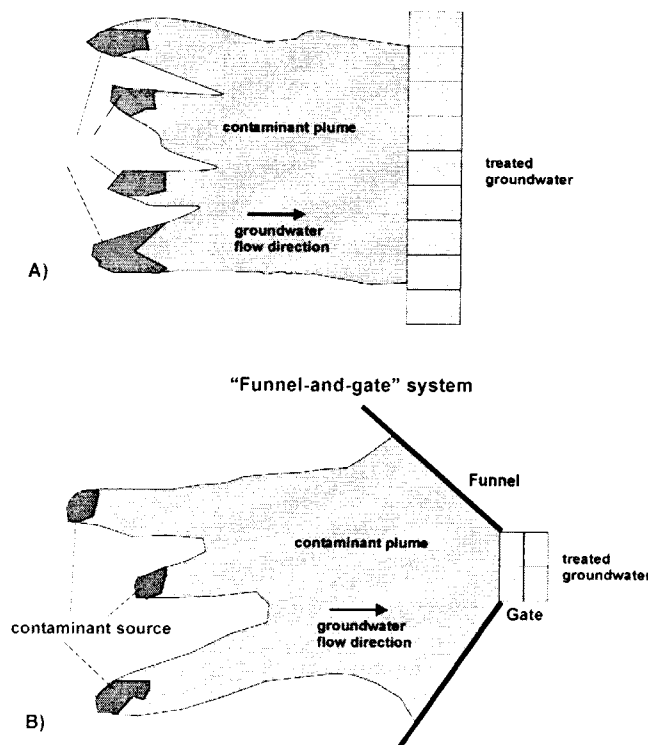


Fig. 20: System sketch "funnel and gate".

- Free product recovery

Non-aqueous phase liquids (NAPLs) consist under other things of liquid phase or pure phase, also known as free product. The liquid phase can be residual (non-drainable) and/or recoverable (mobile, drainable). Light NAPLs (LNAPLs) float on the water table and are free to

move outward from the source area and migrate downgradient along the groundwater flow direction away from the source area, whereas dense NAPLs (DNAPLs) sink since they are heavier than water.

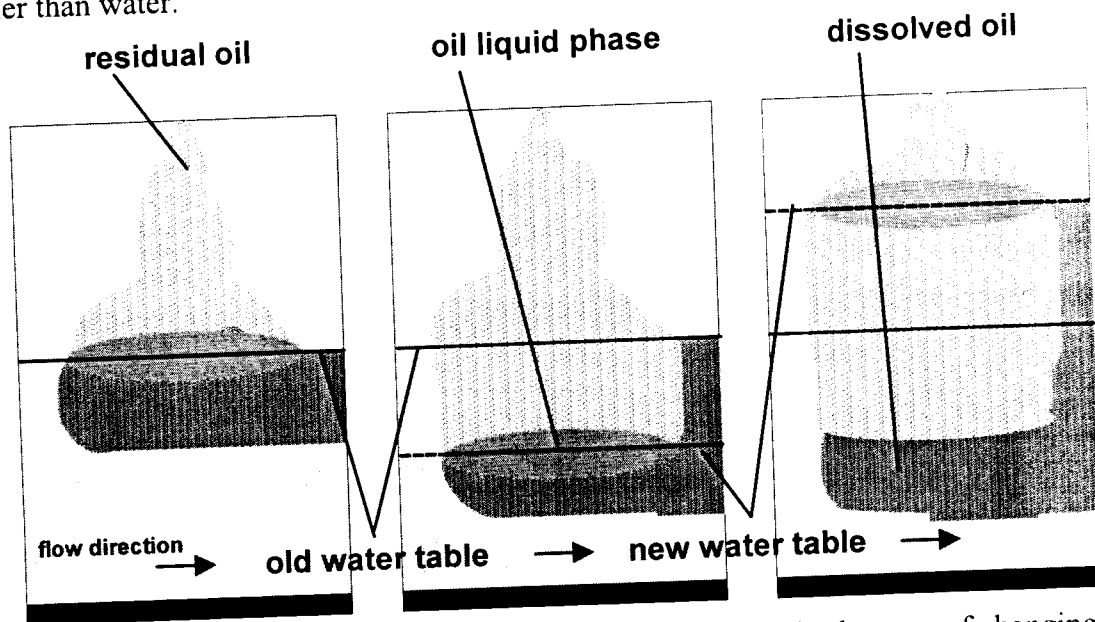


Figure 21: Displacement and smearing of free LNAPL product in the case of changing water table.

Free product on or below the water table serves as a continual source of contamination by dissolving and volatilizing into soils and groundwater. Pumping of recoverable LNAPLs by only one pump results in smearing over a greater vertical distance and thus has as negative consequence an immobility of the now residual contaminants and a larger contact area for dissolution by water (fig. 21). For these reasons, expedited recovery of free product is an extremely important aspect of site remediation. Free product recovery is generally accomplished by installing a trench/drain system, implementing a recovery well system, or by using a dual phase extraction system (fig. 22). Trenching or drain systems can be operated actively through the use of pumps or skimming equipment located in wells or sumps along the trench. Passive operation is accomplished by using the natural hydraulic gradient to recover the free product. Recovery well systems may be designed to recover only NAPL or NAPL and groundwater. Equipment used in recovery wells include skimmers, filter separators, product recovery pumps and groundwater pumps.

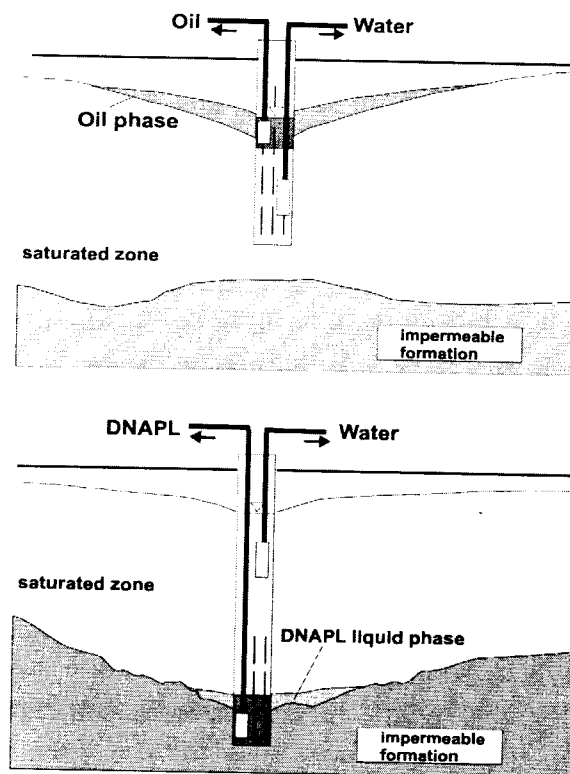


Figure 22: Typical free product recovery dual pump system.

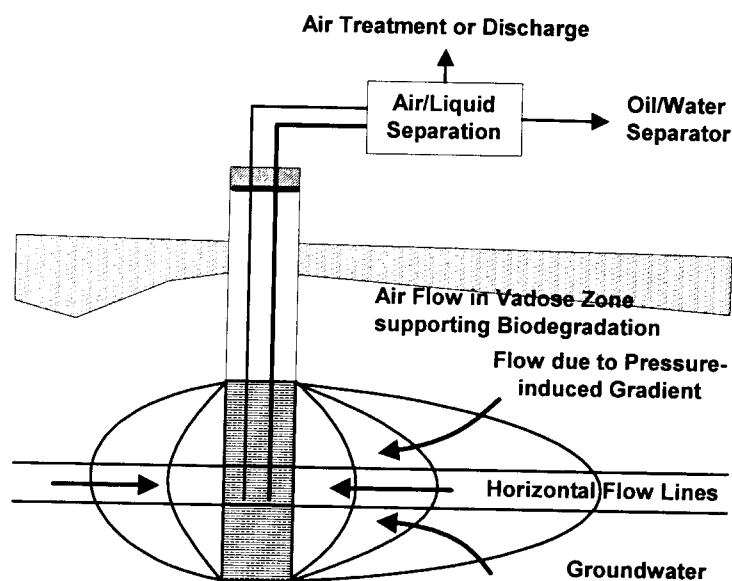


Figure 23: Bioslurping

The new technique of bioslurping (fig. 23) is the adaptation and application of vacuum-enhanced dewatering technologies to remediate hydrocarbon-contaminated sites. Bioslurping combines vacuum-assisted free-product recovery with bioventing (see later) to simultaneously recover free product and bioremediate vadose zone soils. Bioslurping can improve free-product recovery efficiency without extracting large quantities of groundwater. Bioventing of vadose zone soils is achieved by drawing air through the soil via the recovery well. The system is designed to minimize environmental discharge of groundwater and soil gas. When free-product removal activities are completed, the bioslurping system is easily converted to a conventional bioventing system to complete the remediation.

- Soil vapor extraction technologies

Soil vapor extraction is a physical means of removing or reducing concentrations of volatile compounds. The soil vapor process involves applying a vacuum to contaminated soils in the unsaturated zone in order to induce air flow in the subsurface. This technology targets the adsorbed, vapor and free (NAPL) phases of the volatile contaminant present in the unsaturated (vadose) portion of the subsurface acting as a source or reservoir of groundwater contamination during seasonal water table fluctuations or from infiltrating recharge water. For this reason, corrective action systems may likely need to address remediation of unsaturated zone soils as a source of contamination to be effective and complete as a remediation process.

A typical *vapor extraction system* consists of one or more vapor extraction wells connected by a header pipe. The extraction wells can be placed vertically or horizontally, depending on depth to groundwater and other site specific characteristics. The piping system is often placed underground, allowing for more efficient operation during the winter months and also providing extra protection from accidental damage. A blower or a pump is connected to the header system, depending on the flow and vacuum desired. An air/water separator and/or filter is required prior to the vacuum pump in order to protect equipment from moisture and particulates drawn into the system. Discharge from the blower/vacuum pump is either vented to the atmosphere or connected to an off-gas treatment system, depending upon air emissions requirements and the nature and extent of contamination (fig. 24).

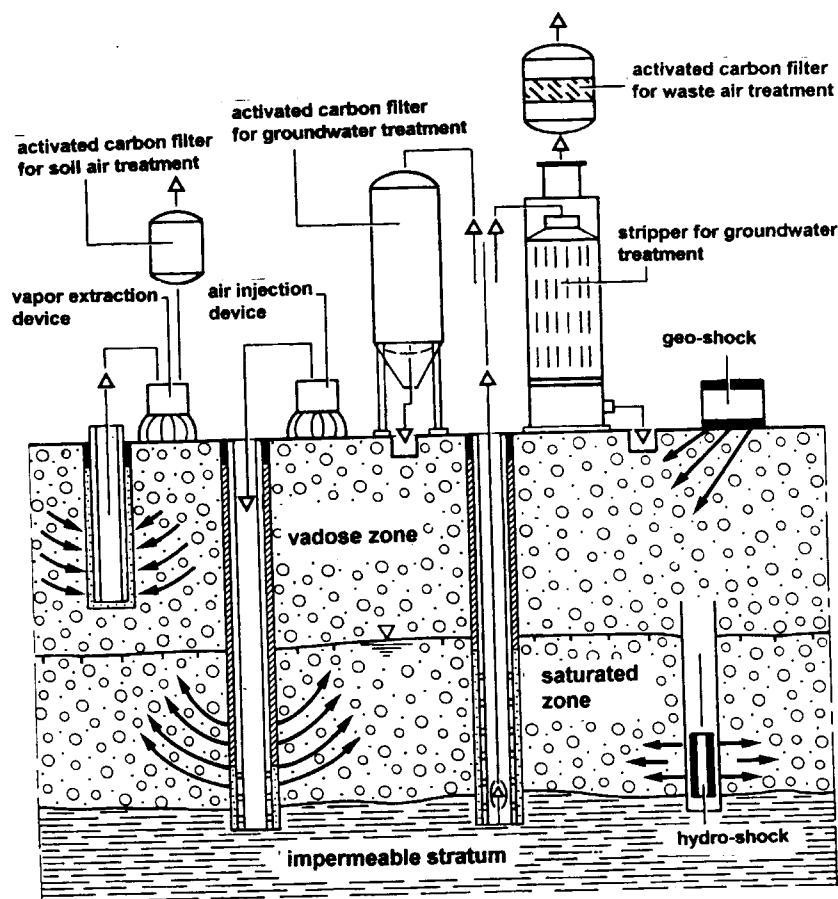


Figure 24: Common removal of DNAPLs from contaminated unsaturated zone.

In some cases, subsurface soil conditions can be modified to facilitate and enhance the application of vapor extraction technology. At some sites it may be necessary to lower the groundwater table in order to enlarge the unsaturated zone. The extracted groundwater may require treatment prior to disposal. To enhance air flow through zones of maximum contamination, it

may be desirable to install air inlet and/or air injection wells. Air inlet wells operate passively, while injection wells force air into the subsurface and can be operated as a closed loop system (i.e. air is injected from the vapor treatment system or directly from the blower). Controlling air flow to an vapor extraction system can also be accomplished by installing a cap or impermeable barrier at the soil surface, potentially widening the horizontal distance under the influence of the extraction wells. The surface may be sealed with plastic sheeting, clay, concrete or asphalt; existing surface structures can also be incorporated as soil caps.

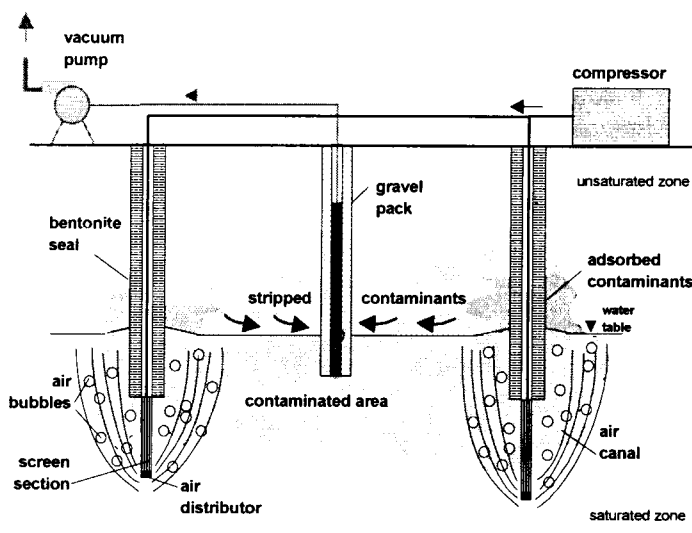


Figure 25: Technique of air sparging or in-situ air stripping.

Commonly used in conjunction with soil vapor extraction systems is the new technique of air sparging or in-situ air stripping (fig. 25), applicable for volatile organic contaminants in relatively moderate to high permeability geologic materials. Gas (usually air or oxygen) is injected under pressure into well(s) installed within the saturated zone to volatilize contaminants dissolved in groundwater, present as non-aqueous phase liquid, or sorbed to the soil matrix. As the injected air travels upward through the water column, bubbles form which remove volatile organic compounds present. Volatilized contaminants migrate upward and are removed upon reaching the vadose zone, typically through soil vapor extraction. This technology allows treatment of vadose zone soils, saturated zone soils and groundwater in the saturated zone.

Implementing air sparging system without soil vapor extraction can potentially create a net positive pressure in the subsurface, inducing contaminant migration into previously uncontaminated areas.

An innovative new technique is thermal enhancement (fig. 26) using steam, heated water, or radio frequency (RF) or electrical resistance (alternating current) to alter temperature-dependent properties of contaminants in-situ to facilitate their mobilization, solubilization, and removal. Volatile and semivolatile organic contaminants may be vaporized. Vaporized components then rise to the vadose zone where they are removed by vacuum extraction and treated.

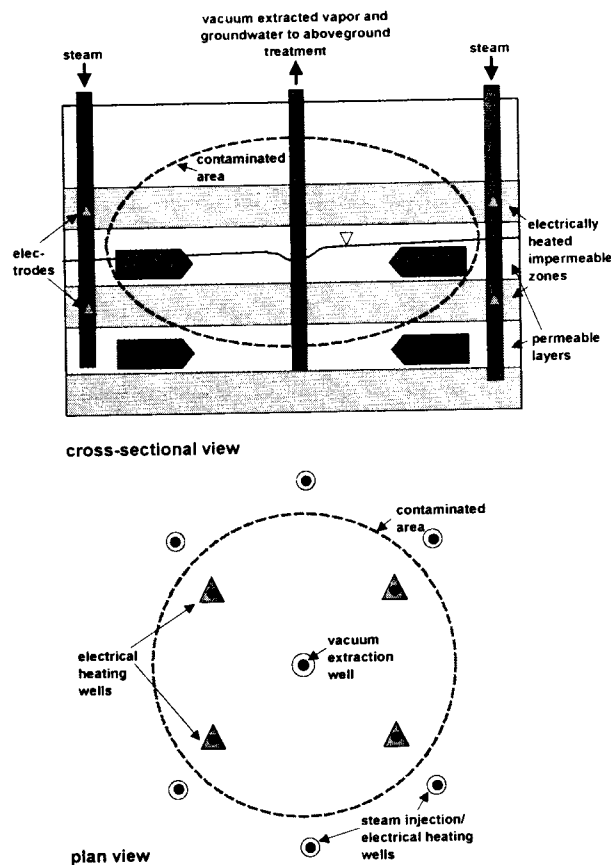


Figure 26: Thermal enhancement technique using steam heating and electrical heating wells to mobilize volatile organic contaminants.

The effect of air stripping can essentially be supported or augmented with other remedial techniques, mostly based on bio- techniques (fig. 27).

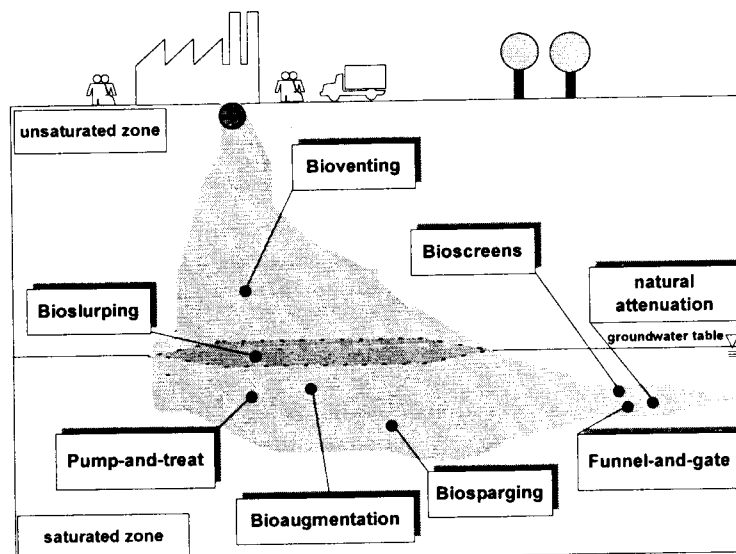


Figure 27: Localization of several in-situ-bio-techniques.

A modern development is the „vacuum vaporizer well“ technology that can be understood as a cross between pump-and-treat and air stripping. The polluted groundwater is stripped in-situ by air in a below atmospheric pressure field maintained by a ventilator. The used air, charged with volatile contaminants, is cleaned using activated carbon. The well produces a vertical circulation flow in the surrounding area which catches the total aquifer (fig. 28). The vertical

velocity compound yields a desired flow through the horizontal structure of an aquifer. A special well with two screen sections is employed, one at the aquifer bottom and one at the groundwater surface. The borehole between the two screen sections should be made impermeable. One well should be used to remediate only one aquifer and should not connect different aquifers.

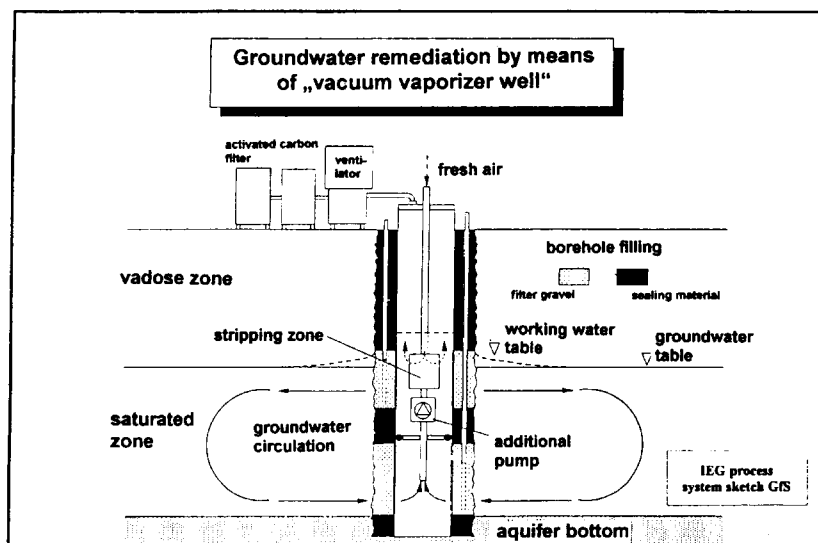


Figure 28: Vacuum vaporizer well.

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