

WATER IN THE BALANCE

No. 1 July 1994

“Soil Vapor Extraction
is not effective for
every site.”

Colorado Water Resources
Research Institute

Colorado
State
University

When is soil vapor extraction right for protecting ground water quality?

Soil vapor extraction is an attractive method for removing contaminants that can exist as vapor in the soil above the water table. Because vapor extraction can potentially treat soil without costly removal, it is an economically attractive option. But, without adequate consideration of the soil and contamination characteristics, vapor extraction methods may be economically infeasible or technically unrealistic.

This issue of *Water in the Balance* will explore current soil vapor extraction technologies and the factors that influence the success or failure of soil vapor extraction systems. First, an open letter on ground water remediation by a prominent researcher puts

remediation technologies into perspective. Then, surface and underground sources of soil contamination are described.

Soil vapor extraction is defined and then discussed in detail in the context of soil characteristics and types of volatile organic compounds that determine the effectiveness of extraction systems. Finally, site investigation methods are presented to provide a comprehensive view of this technology.

The success or failure of a soil vapor extraction system hinges on a host of variables. This issue of *Water in the Balance* provides a starting point for determining if soil vapor extraction is the right technology for a contaminated site. ♠

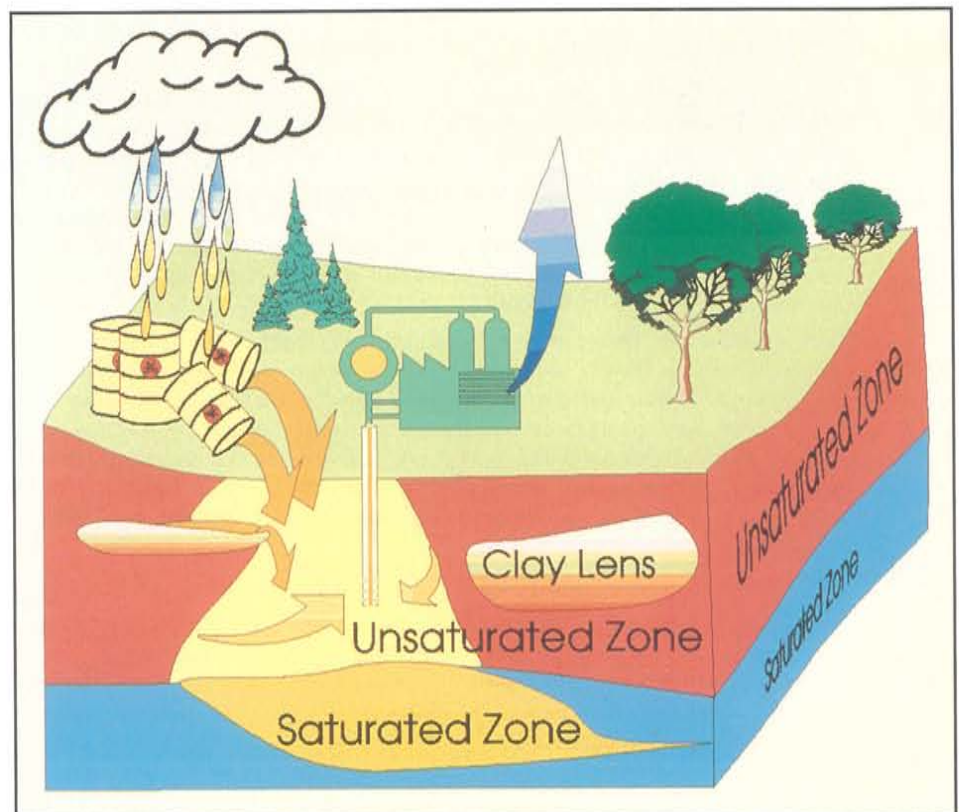


Figure 1: Removal of contaminants using soil vapor extraction.

An Open Letter on Ground Water Remediation

Dear Reader:

A great deal of time, effort and money have been expended in the United States toward the goal of remediation of contaminated ground waters. Such effort was mandated by law long before it was known if restoration of ground water was technically feasible. The restoration mandate also precedes a necessary understanding of all the features of ground water contamination that we now recognize as having important implications for the success or failure of remediation efforts.

The mandate to restore aquifers, essentially to their pre-contamination status, has motivated the appearance of many technologies intended for that purpose. It has also fostered a proliferation of remediation technology vendors, who all too often exaggerate claims for the performance and effectiveness of these technologies. The user community, under pressure to do something, has embraced these technologies without thorough investigation as to the site specific performance that could actually be achieved.

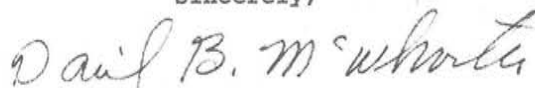
All of this has combined to result in a colossal expenditure with very little return. To this day, there does not exist in the refereed literature a documented case of ground water restoration to maximum contaminant levels in an aquifer originally contaminated with dense, non-aqueous-phase liquids. Instead of a gradual increase in ground water remediation success stories that we might anticipate, we observe more documented failures.

Of course the success or failure of technology at a particular site is tied directly to the standard upon which success or failure will be judged. A typical standard is the drinking water maximum contamination level. To achieve this level often requires that contaminants be reduced by several orders of magnitude in concentration, relative to the source concentrations. Furthermore, such low target concentrations in restored ground water translate to virtually 100 percent source removal. Chlorinated hydrocarbons are among the most common contaminants of ground water, and they are particularly difficult to remove. Even minute quantities left in the subsurface are sufficient to cause continued ground water contamination.

Simply put, there has existed a large gulf between restoration requirements and that which is technologically feasible to achieve. Few have been willing to admit to this conflict. However, empirical evidence is accumulating that makes denial an increasingly indefensible position. We now see regulations, position papers, and guidance documents which recognize the fact that technology is sometimes incapable of achieving that which we desire, no matter how much effort and money are spent. Also observed, is an increased willingness on the part of scientists, engineers, and technology vendors to openly discuss the inherent limitations of technology.

This easing of tension is healthy, productive, and will go a long way toward eliminating wasted time, effort and money in attempting to achieve that which isn't achievable. On the other hand, technological limitations should not become a crutch used to justify no action when there are sensible things that should be done. Reaching an appropriate balance in this regard depends centrally on knowledge of performance effectiveness and applicability of technologies under consideration. It is the goal of this project to contribute to the attainment of this balance by providing an assessment of current soil vapor extraction technology.

Sincerely,



Dr. David B. McWhorter
Engineering Professor
Colorado State University

Sources of Soil Contamination

Contamination in the soil above the water table may include industrial solvents, petroleum products, agricultural chemicals, and household chemicals, to name a few. These contaminants can come from underground or surface sources.



Underground Sources

Underground soil contamination sources include leaks from underground pipelines or storage tanks, municipal landfills, and chemical waste burial sites. Until fairly recently, underground gasoline storage tanks for filling stations were a common soil contamination source.

Contaminants from leaking waste drums and containers located in landfills can combine different

types of contaminants, forming what are sometimes called “Chemical Cocktails.” These combinations of different types of organic compounds can introduce uncertainty into any remediation effort.



Surface Sources

Surface soil contamination sources can include waste ponds, tailing fields, accidental spills, and illegal dumping. Accidental spills and illegal dumping are extremely difficult to prevent or predict.

In the past, it was common practice to discharge some types of industrial chemicals onto the ground surface. For example, as late as the 1960s a common occurrence during industrial construction was to flush

chemical transport pipes with solvents and then allow the mixture to discharge onto the ground. One case, in particular, didn’t become a threat to ground water until twenty-five years after the incident.

“For over 52 percent of the population of the United States ground water is the primary source of drinking water. Among people who supply their own drinking water, ground water accounts for nearly 98 percent of their water (Solley et al, 1988).”

Regardless of the source, ground water is at risk when soil contamination exists above the water table.

For additional information about contaminant hydrology, see Fetter (1993). ♣

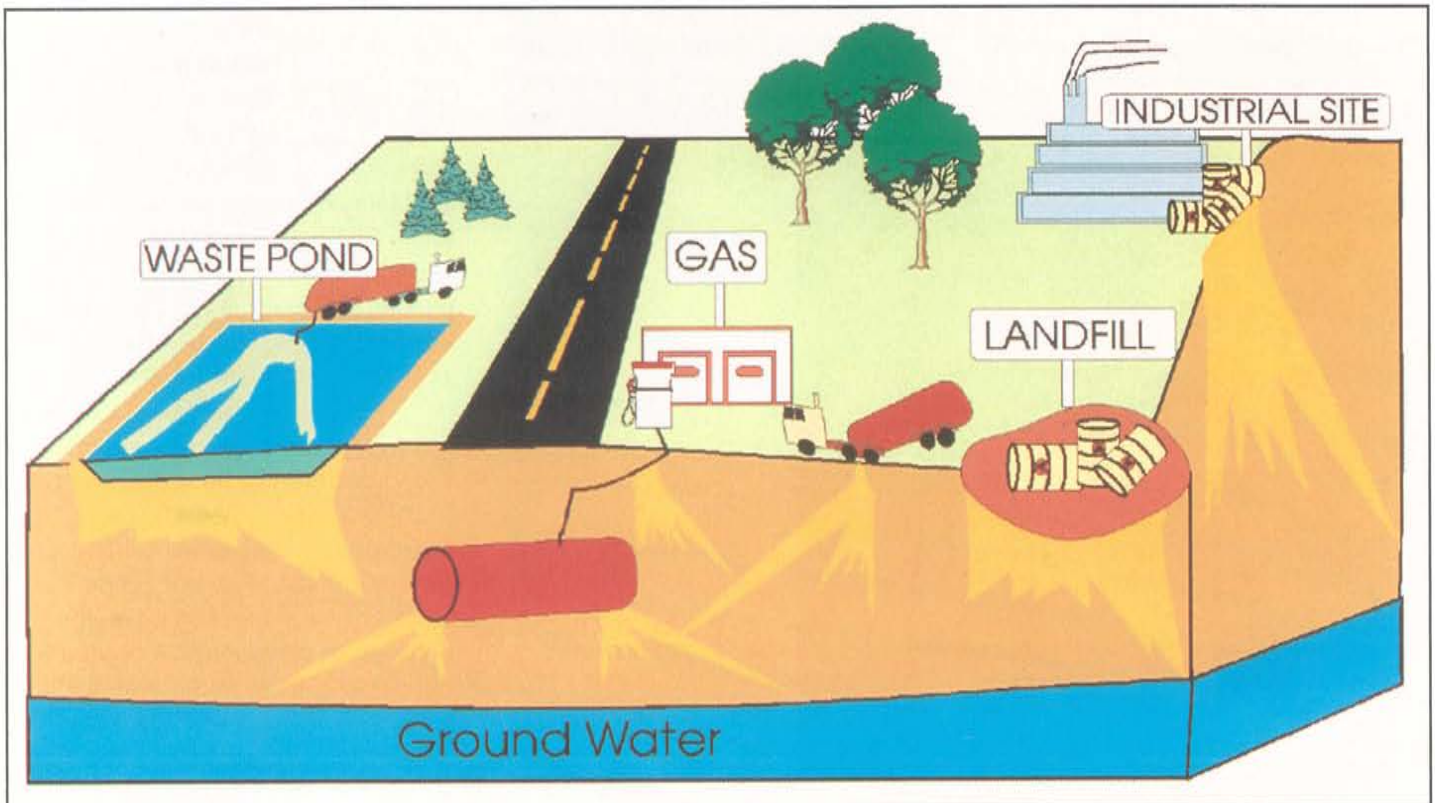


Figure 2: Common sources of contamination in the soil.

Soil Characteristics that Determine the Effectiveness of Soil Vapor Extraction Technology for an Individual Site

Depending on the complexity and the extent of contamination, site soil characteristics will determine if soil vapor extraction is an effective remediation technology.

Some of the soil properties that influence the feasibility of this technology for a particular site will be discussed in this section. It must be emphasized that individual site investigation is critical to the proper application of this technology and that soil characteristics vary greatly between sites.

The success of soil vapor extraction depends on the ability to establish adequate air flow through the contaminated area. Air flow

characteristics in the subsurface depend on soil properties of the unsaturated zone above the water table.



Subsurface Zones

The subsurface is separated into two major zones. These two zones are divided by the water table, with the saturated zone beneath the water table and the unsaturated zone above the water table.

The saturated zone has other geologic formations, but can be visualized as a huge underground reservoir, called an aquifer. An

aquifer is a water-saturated geologic formation that is characterized by the ability of the formation to produce water through wells.

The other subsurface zone is the unsaturated zone where water and air coexist in soil pores. As water infiltrates from the ground surface through the unsaturated zone, a portion of the water is retained in the soil pores. Water can also exist in this zone as pools called perched water.



Removing Contamination

Alternatives for removing contamination from the unsaturated zone include excavation with on-site or off-site treatment or disposal, biological degradation, soil flushing and soil vapor extraction.

Contaminants in the unsaturated zone cannot be removed by traditional “pump and treat” technologies that are commonly used to remove contamination from below the water table. Although soil vapor extraction is analogous to traditional pump and treat technologies, it can only remove contaminants if they are able to exist as a vapor in the unsaturated zone.

The concept behind soil vapor extraction is that it replaces contaminated underground air with clean air from the surface. This concept assumes that compounds contained in the unsaturated zone will become vapors or volatilize. Once volatile, transport of compounds is limited by the soil properties of the unsaturated zone.

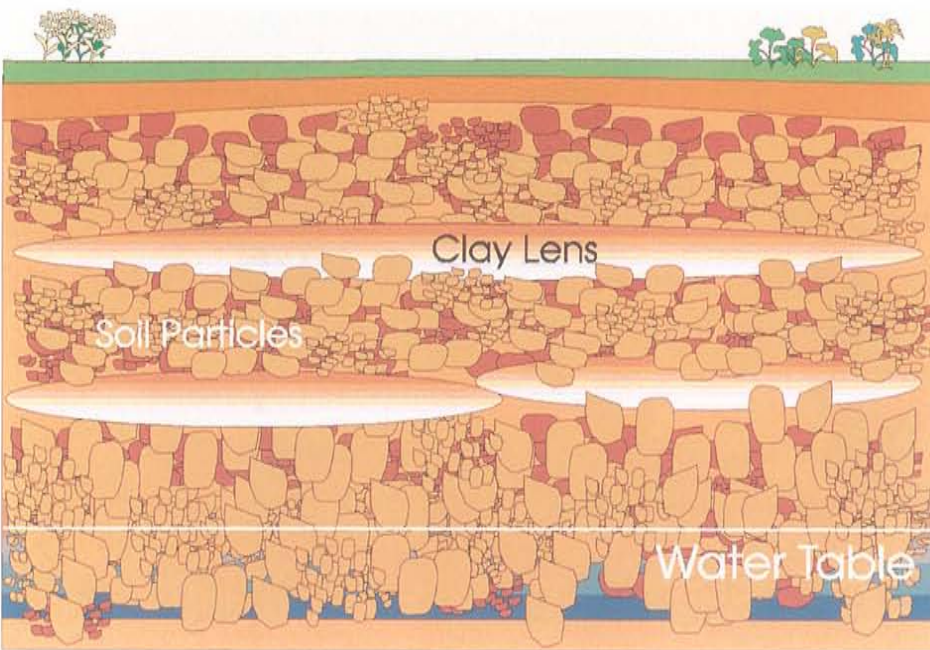


Figure 3: Soil characteristics of the subsurface, indicating the potential complexities involved.



Soil Properties

The properties of a soil structure define the initial effectiveness of soil vapor extraction methods in establishing an air flow to remove volatile organic compounds. The properties of the soil matrix can be defined by the soil's permeability, porosity, particle characteristics and uniformity.

Soil Permeability

Soils with a high permeability will allow air flow more easily than soils with a low permeability.

Permeability depends upon the direction of air flow and soil characteristics. Vertical and horizontal permeability will most likely be different. For example, stream and lake beds tend to deposit geologic formations with high permeability horizontally and low permeability vertically.

The permeability determines not only the direction, but the extent of air flow through soil. For example, a coarse sand with a high permeability allows 100 times more air flow than a fine sand with a low permeability assuming all other factors are constant and conditions are ideal.

“Once volatile, transport of compounds is limited by the soil properties of the unsaturated zone.”

Soil Porosity

The porosity of soil is the volume of void spaces between the soil particles divided by the total volume. Porosity is usually measured in a number of locations and averaged for a soil zone.

Porosity is an important factor in determining permeability, but permeability must be defined along with other soil characteristics. For

example, porosity alone does not consider the interconnection of void spaces, but only the volume of the void spaces. Some researchers prefer the term effective porosity, which takes the degree of interconnection into consideration. Also, a soil matrix with a high porosity may not have a high permeability. For example, a clay soil may have a high porosity, but a low permeability. In comparison, a sandy soil may have a low porosity, but have a considerably higher permeability.

This relationship between porosity and permeability is due to soil particles like clay that have high air flow resistance due to high surface areas. This increase in resistance tends to outweigh any increase in permeability that could be expected with a high porosity.

Uniformity

Uniformity is the measure of the particle-size distribution in a soil sample. A uniform soil is a soil type composed of soil particles of a similar shape and size. A soil with particles of many different sizes is termed well-graded. The uniformity of soil has a great effect on permeability, porosity, and soil moisture content. Well graded soils will tend to have a lower permeability, a lower porosity, and a higher moisture content depending on the soil particle characteristics.

Soil Particle Characteristics

Soil particles come in all shapes and sizes: clay particles tend to be long and flat; sand tends to be coarse-grained; and wind or river-formed rocks are spherical. The shape of soil particles directly affects the characteristics of air flow through soil. This relationship can be measured by determining the surface area to volume ratio for particles.

Clay soils tend to have a higher ratio of surface area to volume than sand. Higher ratios of surface area to volume result in higher frictional resistance to air, slowing down the rate of air flow to near zero.

The principal types of soil particles are classified as clay, silt, sand, gravel, and rock. The sediment in the porous medium will generally be a mixture of these principal soil types.

Table 1: Particle Size Limits of Soil Constituents (Peck et al, 1974).

Soil Type	Size Limit (mm)
Gravel	Larger than 4.75
Coarse sand	4.75 - 2.00
Medium sand	2.00 - 0.425
Fine sand	0.425 - 0.075
Silt and Clay	Smaller than 0.075

In some cases contamination may exist in fractured rock, but flow through fractured rock can be difficult to describe. Since removing contamination depends on the placement of fractures, soil vapor extraction can be difficult to apply.



Homogeneity

Homogeneity of the soil can be thought of as a measure of the spatial distribution of different soil types. This is important to soil vapor extraction because a non-homogeneous soil matrix consists of different kinds of soils with different particle sizes. The degree of homogeneity of the soil matrix can change air flow through a contaminated zone.



Soil Moisture Content

The amount of water contained in the soil influences several design factors of a soil vapor extraction system. These design factors include the air flow permeability of the soil and the rate of diffusion of contaminants through the soil pore space.

In general, soil moisture also decreases the relative permeability of soil to air, due to water occupying soil pore space. Soil moisture is usually greater near the water table.



Depth to the Water Table

Another factor that can determine the effectiveness of a soil vapor extraction system is the depth to the water table. If the ground water is shallow, a soil vapor extraction system may not be feasible. Also, soil vapor extraction air inlets that are near the water table will cause a negative pressure directly above the water and actually raise the water table immediately around inlets, called upwelling.



Surface Features

Surface features can also determine the effectiveness of soil vapor extraction systems. In some contaminated locations, paved surfaces or buildings may be located above the contamination. These features may act as an impervious cap that changes the path of air flow from the surface. In some soil vapor extraction designs surface caps are used to intentionally direct the air flow. Also a "cap" is often placed at the top of a well borehole to impede air flow in the backfill of the borehole. ♣

Diffusion Example

As discussed earlier, soil vapor extraction methods are most efficient in soils that are homogeneous and have a high permeability. The existence of a completely homogeneous soil is very rare. Since gas flow will follow the path of least resistance in a soil matrix, areas of low permeability will tend to divert flow into areas of high permeability. These areas of low permeability control feasibility and the time required to remove contamination from the soil. The following example illustrates this effect.

Consider a silty clay layer sandwiched between two layers of highly permeable sand (figure 4). The soil properties of the silty clay layer include a porosity (f) of 0.4, a water saturation (S_w) of 0.7, an organic carbon fraction (F_{oc}) of 0.005, and a bulk density (ρ_b) of 1.59 gm/cm³. The soil properties of the two sand layers are: $f = 0.3$, $S_w = 0.1$, $F_{oc} = 0.0001$, and $\rho_b = 1.86$ gm/cm³. In this example, trenches are placed on both sides of the contaminated zone, a vacuum is created at the air outlet trench, and the following assumptions are made:

- A horizontal flow through the contaminated zone.
- An initial trichloroethylene equilibrium concentration in the contaminated zone of 200 mg/L.
- No air flow through the silty clay layer.
- One pore volume of air is sufficient to remove contamination from the sand layers.

With these assumptions, the time to remove trichloroethylene from the sand layers is less than four hours. The only process that can remove trichloroethylene from the silty clay layer is diffusion into the sand layers. Now, when diffusion from the silty clay layer is considered, the time to remove 99 percent of the trichloroethylene from the contaminated zone is approximately 445 days!

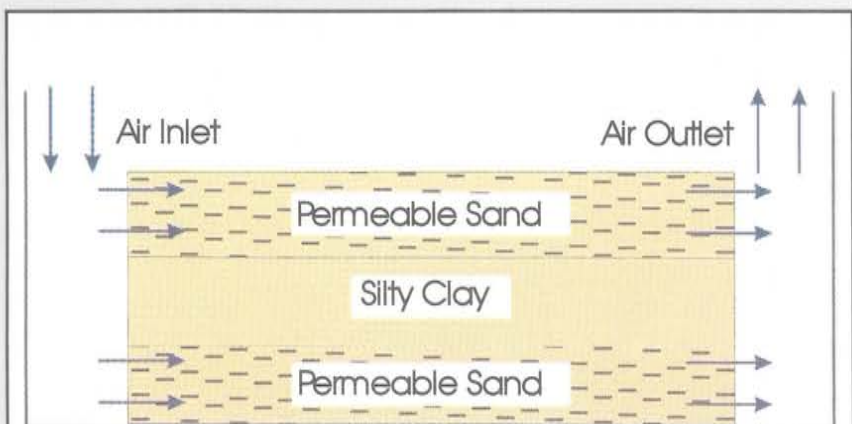


Figure 4: Illustration for the assumptions of the diffusion example (air flow is considered zero for the clay layer).

Removal of Volatile Organic Compounds

A substance must become a vapor to be removed by soil vapor extraction. If a substance exists as a liquid, attached to soil particles or dissolved in water, it must first become a vapor to be removed by soil vapor extraction as illustrated in Figure 5.



Volatility

Volatility is the ability of a substance to become a vapor. It can also be thought of as a substance's ability to evaporate. Volatility is important in determining if a contaminant can be removed by soil vapor extraction, and if so, the rate of removal that can be expected.

Volatility is dependent upon the water solubility of the substance. The more soluble the compound is in water, the less likely it will be to volatilize. Volatility is also temperature-dependent, since higher temperatures cause substances to have a higher vapor pressure.



Volatile Organic Compounds

The requirement that a contaminant be in the vapor state to be removed by vapor extraction creates a class of compounds called volatile organic compounds, or VOCs. Compounds that fall within this category include some of the constituents of gasoline, such as benzene and toluene. Two common examples of VOCs are tetrachloroethene, which is commonly used as a dry cleaning solvent, and trichloroethene, which is commonly used in the computer industry as a degreaser.

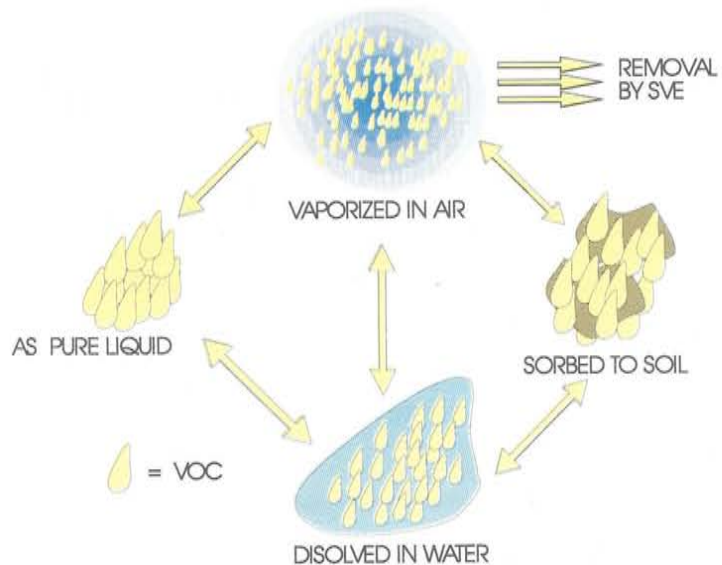


Figure 5: Various states of volatile organic compounds below the ground surface.



Transport

The transport of contaminants through the subsurface is governed by two processes: advection and diffusion. Advection is the process of transporting contaminants as vapors within the air flow created by a soil vapor extraction system. This process can be faster than diffusion. Diffusion is a molecular process of substances moving from areas of relatively high concentrations to areas of relatively low concentrations.



Sorption

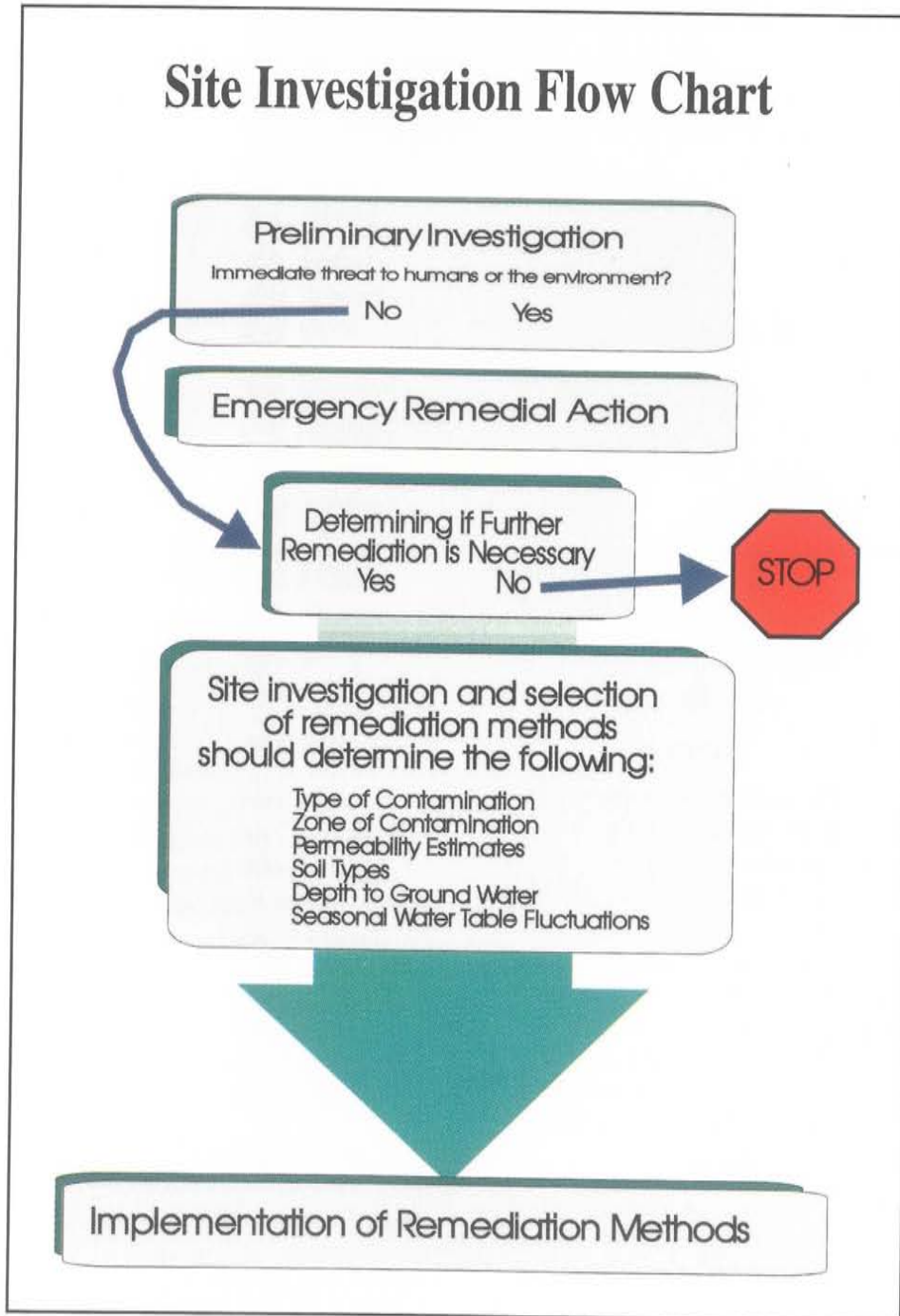
As contaminants move through the unsaturated zone, a certain portion will be absorbed by or attached to soil particles. The attraction of contaminants to the surface of the soil particle is called adsorption. The penetration of the contaminant into the soil particle is called absorp-

tion. Since it is nearly impossible to distinguish between the two processes, the term sorption is used to describe the combination of both processes. Some of the properties of the subsurface that determine the extent of sorption include natural organic matter content, water solubility, and soil type.

“VOCs existing as liquids, sorbed to soil, or dissolved in water must become vapors to be removed by soil vapor extraction.”

Sorption of VOCs slows down their rate of transport through the unsaturated zone, thus increasing the time for removal. The amount of natural organic matter in the soil is the largest determining factor in sorption. The greater fraction of organic carbon in the soil, the greater the retardation of VOC transport. Clay soils generally have greater fraction of organic carbon than other soils, which makes the removal of VOCs from clay soils difficult. ♠

The Site Investigation Process



Once an area has been found to have contamination in the soil, a method of site investigation should be followed to provide information about the immediate danger, long-term effects, and possibilities for remediation technologies.

Site investigation is a critical part of any remediation effort. Some researchers have estimated that site investigation costs could approach actual remediation costs (Johnson et al, 1990a).

For federal remediation sites, specific legal requirements apply to the site investigation and remediation process. These specific requirements are mandated by two federal laws: the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). Generally, CERCLA covers abandoned hazardous waste sites if more than one entity is responsible, and RCRA applies to treatment, storage, and disposal facilities still in operation. In addition to the federal process, state and local governments may have different or additional regulations that apply.

Most of these regulatory guidelines follow five basic steps:

- Preliminary Investigation
- Emergency Remedial Action
- Determining if Further Remediation is Necessary
- Site Investigation and the Selection of Remediation Methods
- Implementation of Remediation Methods



Preliminary Investigation

Upon the discovery of contamination, the first process is the preliminary investigation. This process should provide investigators an opportunity to determine the magnitude of the problem and to determine if there is any immediate threat to human health and/or the environment.

At this stage, any historical information for the site should be gathered and analyzed. This information should be helpful in identifying the contamination's source, the extent of contamination, and the potential risks to water sources.



Emergency Remedial Action

If it is determined that an immediate threat to human health and/or the environment exists, actions should be taken immediately to minimize the hazard. These actions could consist of eliminating the contamination source, removing the contaminated soil, and/or temporary containment technique.

“Not all subsurface contamination sites are created equal (McCarty, 1990).”



Determining if Further Remediation is Necessary

Not all soil contamination sites require additional remediation beyond the initial steps. Also, remediation is not economically or technically feasible at all sites. An assessment of the soil and contaminant characteristics should be made

to determine if additional remediation is necessary.



Site Investigation and the Selection of Remediation Methods

The site investigation and the selection of remediation methods begins when it has been determined that remediation is necessary for a site. The main goal of this step is to determine what steps should be taken for site remediation.

The purpose is not to answer all the site-specific questions, but to obtain just enough information to be able to make informed decisions. At this step, possible long-term human health and environmental risks are assessed and appropriate response alternatives are evaluated.

During the site investigation a number of different techniques can be used to gather data. Wells can be drilled, soil gas monitored, and soil borings taken to sample the type of contamination, the soil characteristics, site geology and other useful information. The extent of the investigation should be determined on a site-by-site basis depending on information gained in the preliminary investigation.

Wells can be helpful in determining the water table elevation and the extent of the contamination near the surface of the ground water. Soil gas monitoring is done by extracting and measuring vapors from the subsurface, and can provide information on the vertical and horizontal extent of the contamination.

Soil borings can be used to determine total concentrations of contaminants and soil characteristics. Obtaining samples at individual points should not be expected to be indicative of the entire site characteristics.

The remedial investigation process should be repeated until the following characteristics can be determined or adequately estimated:

- Type of Contamination
- Zone of Contamination
- Permeability Estimates in both the Saturated and Unsaturated Zones
- Soil Types
- Depth to Ground Water
- Extent of Seasonal Fluctuations of the Water Table

“The purpose of site investigation is not to answer all the site-specific questions, but to obtain just enough information to be able to make informed decisions.”

With the current high cost of chemical analysis, it is important to intelligently select which vapor samples should be analyzed and what analysis should be preformed. Costs can be minimized by using field screening tools such as vapor meters and portable gas chromatographs. At the minimum, visual observations or changes in odor should be recorded with samples.

Once site data have been obtained, additional field testing and analysis should take place to determine the expected permeability of the soil, the initial contaminant vapor concentration, and other factors for the design of the soil vapor extraction system.

In most cases, as the concentration of the contaminant is reduced by vapor extraction, the efficiency will taper off and will eventually be limited by diffusion in areas of low permeability. Therefore, the soil characteristics of a site are critical in determining the long-term effectiveness of soil vapor extraction methods.

Also worth consideration is that soil vapor extraction may be one of

many different processes used in a given site. Ground water remediation techniques may be used below the water table, along with soil vapor extraction and other methods such as biodegradation or flushing to achieve water quality goals above the water table. The positive or negative impact of a soil vapor extraction system on these other remediation techniques (and vice versa) should be evaluated.

Vapor extraction systems may have some inherent negative impacts that should be evaluated before the

installation of a system. In some cases the negative pressure caused by an extraction system can cause the water table to rise or upwell. When the water table rises it may clog the extraction system, mix with contamination in the unsaturated zone, or bring additional contamination from the saturated zone. Another possible negative impact of an extraction system is that it may be a means to transport contaminants from unwanted areas that were not included in the remediation plans.



Implementation of Remediation Methods

Due the inherent uncertainty in determining soil and contamination characteristics of the subsurface, additional information is usually obtained during the implementation that can be used to reassess the remediation techniques. ♠

Estimating Costs

The best way to estimate the expected cost of any remediation technology is on a cost-per-benefit ratio; for example, cost-per-pound of contaminant removed. In most cases this cost estimation method cannot be done until a system is operational and data are collected.

Determining the cost of a soil vapor extraction system on a per-item basis can at best be a rough estimate of the actual costs, but may be the only option available during site investigation. Some of the cost considerations are listed below:

- The drilling of observation and extraction wells is highly dependent on the depth, geology and the type and diameter of the well.
- The costs for digging trenches for pipe burial depend on depth, location and soil type.
- Polyvinyl chloride (PVC) piping is normally used for soil vapor extraction systems. Costs will depend on the length of the pipe, the diameter, and the number and type of joints and valves.
- The capital costs of shelters, pipe insulation, vapor liquid separators, and a vapor treatment system.
- Operation and maintenance costs include gas treatment systems, power costs for blowers, and sampling costs.

A problem with a cost-per-item estimation is that different remediation methods cannot be evaluated except by determining a rough capital-cost estimate and comparing amounts.

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About the Colorado Water Resources Research Institute and Water in the Balance

The Colorado Water Resources Research Institute (CWRRI) exists for the express purpose of focusing the water expertise of higher education on the evolving water concerns and problems being faced by Colorado citizens. CWRRI strives to constantly bring the most current and scientifically sound knowledge to Colorado's water users and managers. For more information about CWRRI and/or the water expertise available in the higher education institutions in Colorado, please contact CWRRI at the address below or by phone or fax:

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"Water in the Balance" has been created in the spirit of informing the public about complex water management issues. This initial issue addresses the role of soil vapor extraction in ground water remediation. Some remediation efforts in the United States have been criticized for taking too long, costing too much, and accomplishing too little. It is hoped that by presenting information about the still evolving technology of ground water remediation, more appropriate uses of this evolving technology will become more common place.

This issue of Water in the Balance was prepared for the Department of Energy by the Colorado Water Resources Research Institute. This document was written by Robert W. Lange, David L. Barnes, David B. McWhorter, and Robert C. Ward. Preparation of this document was made possible by funding from the Department of Energy. The contents of this publication do not necessarily reflect the views and policies of the Department of Energy, nor does the mention of trade names or commercial products constitute endorsement by the United State Government.



Colorado Water Resources Research Institute
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