Phytoremediation of Volatile Organic Compounds in Groundwater: Case Studies in Plume Control

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Prepared by

Amelie Van Den Bos

National Network of Environmental Management Studies Fellow

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NOTICE

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Phytoremediation Pilot Study at Aberdeen Proving Ground, Maryland (Hirsh, 2002)

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FOREWORD

The use of plants to remediate contaminated soil and groundwater constitutes an emerging technology that has generated a great deal of interest. EPA's Technology Innovation Office (TIO) provided a grant through the National Network for Environmental Management Studies (NNEMS) to assess the field performance of phytoremediation technologies to clean up volatile organic compounds in groundwater. This report was prepared by a graduate student from Virginia Polytechnic Institute and State University during the summer of 2002. It has been reproduced to help provide federal and state project managers responsible for hazardous waste sites with information on the current status of this technology.

This report provides a basic orientation and current status of phytoremediation for shallow groundwater. It contains information gathered from a range of currently available sources, including project documents, reports; periodicals, Internet searches, and personal communication with involved parties.

References for each case study are provided immediately following the case study. While sources are referenced as footnotes throughout the text, a comprehensive list of all documents (organized alphabetically) and individuals (listed by organization or company) that contributed to the writing of this report is available in the bibliography at the end of the report.

About the National Network for Environmental Management Studies (NNEMS)

NNEMS is a comprehensive fellowship program managed by the EPA's Office of Environmental Education. The purpose of the NNEMS Program is to provide students with practical research opportunities and experiences.

Each participating headquarters or regional office develops and sponsors projects for student research. The projects are narrow in scope to allow the student to complete the research by working full-time during the summer or part-time during the school year. Research fellowships are available in Environmental Policy, Regulations, and Law; Environmental Management and Administration; Environmental Science; Public Relations and Communications; and Computer Programming and Development.

NNEMS fellows receive a stipend at a level determined by the student's level of education, the duration of the research project, and the location of the research project. Fellowships are offered to undergraduate and graduate students. Students must meet certain eligibility criteria.

The report is available on the Internet at www.clu-in.org.

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Purpose

Trichloroethene (TCE) and tetrachloroethene (PCE) are the most prevalent groundwater contaminants in the United States.[1] This paper discusses how various plant species have been used to clean up these contaminants and other volatile organic compounds (VOCs) contaminating groundwater at several sites. In addition to a technology overview, this report provides insight into the field applications of phytoremediation, and discusses the technology performance as well as new developments and findings in this subject matter. The Appendices list information on 55 planned and ongoing phytoremediation projects addressing VOC-contaminated groundwater.

Laboratory studies have shown that phytoremediation of VOCs in groundwater has great potential. It is the purpose of this paper to summarize the status of this technology as applied to VOCs in the field. Following the Technology Overview, the focus of the report is a compilation of case studies implemented by scientists from a variety of organizations, government, academia, and the private sector.

Technology Overview

Phytoremediation is an emerging technology that involves the use of plants to remove organics and metals from soil and groundwater. Building upon plants' natural tendency to absorb organic and inorganic substances from the ground, phytoremediation uses a natural mechanism as an innovative technology for environmental remediation.

Phytoremediation of contaminated groundwater encompasses several mechanisms, which often occur simultaneously and lead to contaminant removal, degradation, or sequestration. Definitions of these terms tend to vary between sources; however, for the purposes of this report, descriptions of in situ phytoremediation mechanisms are as follows:

Rhizofiltration	The uptake of contaminants in water by absorption into plant roots
Phytostabilization	Usually refers to the immobilization of contaminants in the soil, but in some cases is also applied to water[2]
Phytodegradation	The degradation of organic contaminants within the plant
Rhizodegradation	The degradation of organic contaminants in the roots
Transpiration	Loss of water from the stomata of a plant leaf
Diffusion	The release of a contaminant through the plant stem/tree trunk

[1] Collins et al., 2002.

[2] Hauser et al., 1999.

Phytovolatilization The release of contaminants via transpiration and diffusion

As reflected in the above definitions, some plants are capable of more than water and contaminant uptake, and can also biodegrade, volatilize, and immobilize contaminants.

Due to its versatility, phytoremediation can easily be combined with other remediation efforts to maximize site clean-up results. Phytoremediation can complement more traditional methods for groundwater treatment, such as non-reactive barriers (slurry walls) and "pump-and-treat." This report will highlight the ability of phytoremediation to control groundwater movement hydraulically and to contain or capture a VOC contaminant plume, when used in conjunction with other technologies.

Hydraulic Control

Deep-rooted trees called phreatophytes are capable of reaching and removing large amounts of water from the ground through transpiration. Trees such as cottonwoods (poplars) or willows can transpire more than their total water content on a hot sunny day. Transpiration is influenced by plant density, leaf area index, radiant solar energy flux, depth to groundwater, temperature, relative humidity, and wind speed. Thus, depending on site conditions, the natural water consumption of trees can be exploited to influence and even control groundwater movement, resulting in contaminant plume capture.

Hydraulic influence can be evidenced by a decrease in water table elevation (even on a diurnal basis). Groundwater fluctuation can be measured by pressure transducers installed in wells located in the planted area. Groundwater use can also be monitored by indirect methods, such as transpiration estimates based on sap flow, leaf area, or meteorological data and contaminant mass reduction.[3] To demonstrate hydraulic containment of the contaminant plume, however, it is necessary to compare groundwater samples obtained in similar seasons from several years.[4]

Depending on the transmissivity of the aquifer (a function of its hydraulic conductivity and thickness), a cone of depression can form in the groundwater underneath an individual tree or under an entire plantation area.[5] This phenomenon was documented at the Aberdeen Proving Ground project, and resulted in a reversal of groundwater flow at that site during the summer months. On the other hand, in areas with clayey soils, groundwater uptake by trees may result in a mounding effect. Cones of depression can be difficult to identify if there is a topographic (and hydraulic) high point at the project site.

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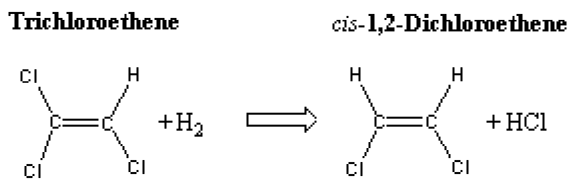
[3] Landmeyer, 2001.

[4] Ferro et al., 2002.

[5] Landmeyer, James. U. S. Geological Survey. Personal Communication, August 20, 2002.

Phytoremediation-Enhanced In Situ Bioremediation

A more active process than monitored natural attenuation, phytoremediation has also been used as a mechanism to augment natural degradative processes. Enhanced in situ bioremediation refers to the use of plants to increase the microbial population in the contaminated soil and groundwater by providing the necessary nutrients, moisture, and electron acceptors. Highly chlorinated VOCs (such as PCE and TCE) are best degraded anaerobically, while end products such as dichloroethene (DCE) and vinyl chloride are best dechlorinated aerobically. Through the production of root exudates as well as root decomposition, the presence of trees can promote a change in subsurface conditions from an aerobic to a mostly anaerobic state. Microorganisms then proceed to break down organic contaminants (such as TCE and its products) via reductive dechlorination. Reductive dechlorination of TCE to cis-1,2-DCE occurs by the following mechanism:



The complete degradation pathway for the process is:

$$\text{TCE} \rightarrow \text{cis-1,2-DCE} + \text{HCl} \rightarrow \text{vinyl chloride} + \text{HCl} \rightarrow \text{ethane} + \text{HCl}$$

Evidence of rhizodegradation via reductive dechlorination occurring in the soil and groundwater underneath the trees can be found by monitoring for increased microbial populations, lower dissolved oxygen concentrations, higher concentrations of reductive dechlorination breakdown products (DCE and vinyl chloride), and higher dissolved carbon concentrations. In addition, sulfide concentrations, methane production, ferrous/ferric iron ratio, and hydrogen gas generation can be indicators of low redox potentials, conducive to reductive dechlorination.

The Carswell Naval Air Station phytoremediation site has collected the types of data mentioned above since 1996. Results of phytoremediation-enhanced in situ bioremediation, as well as hydraulic control, at this site will be provided in the Field Studies section of this paper, and will also be evaluated in the Discussion at the end of the paper.

Modeling

Modeling programs such as MODFLOW are often used in the preliminary design stages of a phytoremediation project, and later after project implementation, to evaluate progress and optimize performance. Modeling programs have been effective in predicting contaminant removal rates as well as simulating the fate and transport of contaminant plumes and groundwater flow.

Groundwater flux can be estimated using Darcy’s Law:

$$Q_a = K \cdot I \cdot A$$

where K = hydraulic conductivity (L/t)
I = hydraulic gradient (dimensionless)
A = cross-sectional area of the plume (L^2)

Two and three-dimensional capture zone calculations can also be used to characterize the plume geometrically. Based on this information, Analytical Element Method (AEM), numerical, and flow simulation models can be generated. Applications of these models will be discussed in greater detail in the field studies presented later in this paper.

Tree Selection and Planting Methods

Poplar and willow trees can be planted as whips, which are sections of one-year-old stems (about one inch in diameter and 18 inches long) harvested from branches during the dormant season.[6] "Poles" (non-rooted cuttings that are several feet longer than whips) or one to two-year-old transplanted trees (with bare, burlapped, or potted roots) may also be used. Larger, rooted trees tend to be more expensive than cuttings, but can be planted at sites where there is a need to see faster results.

Planting density also factors into the rate of contaminated groundwater removal. The amount of spacing between trees determines the time of leaf canopy closure, at which the transpiration rate of the trees (and thus contaminant removal) is maximized. Planting trees too close together for quicker canopy closure, however, can limit sunlight and inhibit tree growth. Because transpiration rates are factors of tree growth and canopy closure, project planning should include a tree configuration that maximizes the number of trees in an area at the same time as it maximizes the spacing between trees. Depending on the remediation timeframe, budget, and area available, closer or wider spaces may be selected.

In order to successfully remove contaminants from groundwater, tree roots must extend far enough to physically reach the contaminants. Hybrid poplars are phreatophytes that are commonly used in field studies for this reason. Not only does this species grow in a wide range of climates, its properties are also readily modified by cross-breeding. Other criteria that affect plant selection include soil type and contaminant type. Native tree species are often considered for phytoremediation projects because of their inherent site-suitability. Variety in tree species is desirable because it increases the plantation's chances of survival.

Soil moisture, soil temperature, density, and oxygen concentration can affect root growth. Various cultivation practices such as tilling can be used enhance root development. Tilling refers to the plowing of a field for the planting of rooted and non-rooted trees. Not only does the plowing aerate and loosen the soil, it also reduces the initial competition of the trees with weeds. Other methods of weed control include mulching and spraying with herbicide.

[6] Rock et al., 2002.

Depending on the depth to the saturated zone, soil type, tree type, and the project budget, the possible planting methods (in order of least to most expensive) include: dibble-bar planting, trenching, and augering. Dibble-bar planting refers to the use of a dibble-bar tool to plant 1.5 foot whips into hard soil. Planting by this method can be completed rather quickly at minimal expense, but trees may require irrigation for the first few years to ensure adequate access to water.[7]

Trenching is another planting method, where deep trenches are dug to create a preferential pathway for roots (Figure 1). Rooted trees or cuttings are then inserted, and the trench is backfilled with soft material (generally topsoil, compost, or peat).

Figure 1. Trenches at Carswell site (Rock, 2002)

In dry places, where the saturated zone is less than eight feet below the ground surface, boreholes can be drilled and 6 to 12 foot "poles" or bare-rooted stock can be inserted directly into the moist sediment. Boreholes can then be filled with a porous medium, leaving about a foot of the tree exposed above ground. Roots develop along the pole, leading to deep-rooted trees that often do not need to be irrigated.[8]

Augers also can be used to drill deeper holes into the ground (up to 40 feet), which can then be backfilled with sand (Figure 2). Poles are planted, leaving up to four feet above the surface. Disadvantages to drilling holes include its expense, as well as the longer length of time required for planting.

Figure 2. 10 ft hole augered through soil, rock, and concrete at Ashland site, 2000 (Photo courtesy of Ecolotree)

Monitoring

Periodic monitoring of a project over several years is necessary for purposes of comparison. Groundwater sampling at monitoring wells helps to determine if the contaminant plume is increasing, decreasing, or remaining the same.

[7] Rock, U. S. Environmental Protection Agency. Personal Communication, August 12, 2002.

[8] Ferro et al., 2002.

Assessing the effectiveness of phytoremediation often depends on indirect measures. In addition, the lag time between when a system is installed and when it is fully operational should be taken into account when evaluating the system. Full root development and canopy closure both may take several years to affect results.[9]

Figure 3 indicates several means of monitoring a phytoremediation system, once it is in place. Case studies described in the subsequent section will provide project results based on similar monitoring methods.

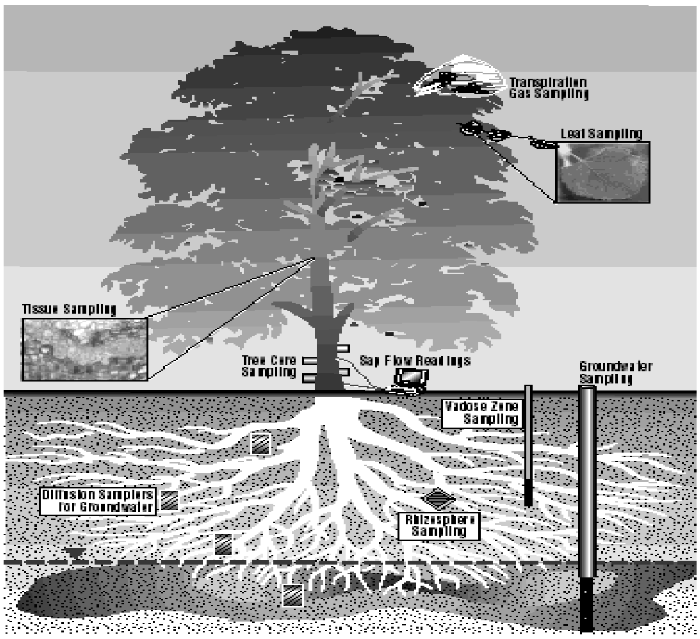


Figure 3. Phytoremediation system monitoring techniques (Hirsh, 2002)

Comprehensive Monitoring

- Transpiration Gas
- Transpiration Rate
- Tree Tissue
- Rhizosphere
- Microbial Activity
- Soil Conditions
- Weather
- Groundwater Hydrology

Benefits of Phytoremediation

One of the main advantages of phytoremediation is that it generally causes little environmental disturbance compared to traditional remediation methods. Vegetation used for phytostabilization prevents flooding and erosion, protects topsoil, and enhances ecosystem restoration efforts. Phytoremediation also tends to be a popular remediation technique because it produces an aesthetically pleasing site.

From an economic perspective, phytoremediation's appeal is due to its reputation as a low-cost technology, with system costs about 50-80 percent less than remedial alternatives.[10] For a comprehensive cost estimate of a phytoremediation project, the following factors must be taken into account:

[9] McLinn et al., 2001.

[10] USEPA, 2000.

<u>Design costs</u>
- Site characterization
- Work plan and report preparation
- Treatability and pilot testing

<u>Installation costs</u>
- Site preparation
  - Facilities removal
  - Debris removal
  - Utility line removal/relocation
- Soil preparation
  - Physical modification: tilling
  - Chelating Agents
  - pH control
  - Drainage
- Infrastructure
  - Irrigation System
  - Fencing
- Planting
  - Seeds, plants
  - Labor
  - Protection

<u>Operating costs</u>
- Maintenance
  - Irrigation water
  - Fertilizer
  - pH control
  - Chelating agent
  - Drainage water disposal
  - Pesticides
  - Fencing/pest control
  - Replanting
- Monitoring
  - Soil nutrients
  - Soil pH
  - Soil water
  - Plant nutrient status
  - Plant contaminant status
  - Tree sap flow monitoring
  - Air monitoring
  - Weather monitoring

(USEPA, 2000)

The domestic market for phytoremediation of organics in groundwater was valued at only $21 to $42 million this year. However, the market is projected to increase to $40 to $80 million by 2005.[11] Market projections reflect the common opinion that phytoremediation is a technology that is on the rise and will become more prevalent in the future.

Drawbacks of Phytoremediation

There are several limitations to phytoremediation. Because every hazardous waste site is unique, choosing the appropriate plant species to use can be difficult. Sites with multiple contaminants dissolved in groundwater may not be good candidates for phytoremediation, because while certain plants may be able to tolerate some contaminants, they may not be able to tolerate others. Also, the length of time required for contaminant removal can be a disadvantage to phytoremediation, as compared to other, more traditional cleanup technologies.[12]

Sites with high concentrations of contamination can also be too toxic for phytoremediation to be effective. Areas with widespread, low to medium level contamination are the best candidates for phytoremediation. Climatic factors such as temperature, amount of precipitation, and sunlight must also be taken into account in addition to important soil characteristics such as pH and water

[11] Glass, 1999.

[12] USEPA, 2000.

content.[13] Depth to groundwater may also be a limiting factor, since trees have been shown to be most effective at locations where the depth to groundwater does not exceed 12 feet.[14]

Selecting phytoremediation at a contaminated site may require more technical information than is usually available after a remedial investigation. Site-specific hydrogeological and contaminant transport data are not routinely collected.[15] This lack of data can lead to a poorly designed and poorly implemented project, which compromises the potential effectiveness of the plants and the site clean-up.

Lastly, the fate of contaminants after plant uptake is a subject that has to be addressed with further study. Low to no contaminants have been detected in air in or around phytoremediation sites, while larger fractions have been found in tree sap and tissue. Research thus far has not been able to definitively account for the fate of the entire contaminant mass estimated to have been removed from groundwater. A better grasp of how phytodegradation, transpiration, and diffusion processes affect the fate of contaminants would represent a major milestone in the acceptance of phytoremediation as a proven remediation technology.

Summary

As indicated in the above sections, phytoremediation projects are reliant upon a variety of factors, from tree survival to regular site monitoring, for their success. Because of the complexity of the technology, it is often difficult enough to assess the value of this innovative method of remediation at a single site, let alone prove the usefulness of this technology overall. The subsequent section presents descriptions of and results from several of the oldest phytoremediation projects in the United States, implemented between 1996 and 1998. It is hoped that this information will provide the appropriate private companies, government regulators, and university researchers with a better understanding of what is going on in the field today and what developments to look for in the future.

[13] USEPA, 2000.

[14] Eberts et al., 2003.

[15] Rock et al., 2002.

Selected Field Studies

Since the success of phytoremediation efforts tends to be very site-dependent, sharing information through case studies can be particularly helpful for professionals who are considering or are already implementing phytoremediation projects. The summaries included in this section include information on conditions at specific sites (contaminant concentrations, plume depth and dimensions), project implementation details (objectives, design), results to date, and references of available written material on the project.

Charts of all ongoing and anticipated phytoremediation projects that the author has identified (55 total) are also provided in the appendix of this report. These charts supply valuable reference information to other relevant studies, including a point of contact for each project.

The number of field studies that are currently being implemented has increased considerably since five years ago (see Appendix). Many of these projects have only been in operation for two to three years; therefore results are still too preliminary to discuss. Other projects, however, have now reached maturation, and researchers have a variety of data that they can use to evaluate the progress of phytoremediation at their sites. Some of these projects, such as the Aberdeen Proving Ground site in Maryland, the Carswell Naval Air Station site in Texas, and the Edward Sears Property site in New Jersey, have been designated by the North Atlantic Treaty Organization's Committee on Challenges of Modern Society (NATO/CCMS) as innovative remedial technology demonstration sites, and these (in addition to others) will be examined in detail below.

J-Field, Aberdeen Proving Ground, Edgewood, Maryland

SITE DESCRIPTION

The five-year field demonstration at J-Field, Aberdeen Proving Ground is one of the most extensively studied phytoremediation projects in the United States. The site consists of a one-acre area with 1,1,2,2-tetrachloroethane (1,1,2,2-TeCA) and trichloroethene (TCE) contaminated soil and groundwater. One hundred eighty three hybrid poplar trees (*P. deltoides x trichocarpa*) were planted in 1997, with the dual objective of containing the VOC plume and reducing contaminant mass through transformation and transpiration.

Trees were planted 10 feet apart, in a U-shaped configuration. At first, they were planted using plastic sleeves to promote downward root growth and groundwater uptake. After excavation and assessment, however, this method was found to restrict the lateral root growth necessary to prevent trees from blowing over during storm events and was thus abandoned in 1998. Boreholes were used with more satisfactory results during a later round of planting (2002), which added about 150 more hybrid poplars as well as 450 native trees (species such as tulip trees, silver maples, evergreen hollies, loblolly pines, oaks, and willows) to the site.

Conventional remediation technologies such as soil washing, soil vapor extraction, groundwater pump-and-treat, and groundwater circulation wells have been tested at J-Field, but the presence of unexploded ordnance, a low permeability aquifer, and the continuously-fed VOC plume have hampered the progress of these remediation efforts. The J-Field site has several attributes that make it suitable for phytoremediation, however. First, the site is inaccessible to the public and has no groundwater users, which means the length of time to full contaminant clean-up is more flexible. Additionally, the low groundwater velocity and presence of the freshwater marsh to help degrade VOCs are factors that enhance the effectiveness of phytoremediation.

Combining hydrological data such as precipitation (45 inches per year on average) with other information such as soil characteristics (variable texture – fine sand and clayey silt) allowed researchers to model the potential for hydraulic containment of contaminated groundwater (Figure 4). The model uses site-specific inputs on hydrology, transpiration and biodegradation, and takes into account factors like hydraulic conductivity of sediments in the aquifer. Data analysis with MODFLOW was supplemented by another modeling tool, earthVision, which allowed for aquifer and plume characterization.

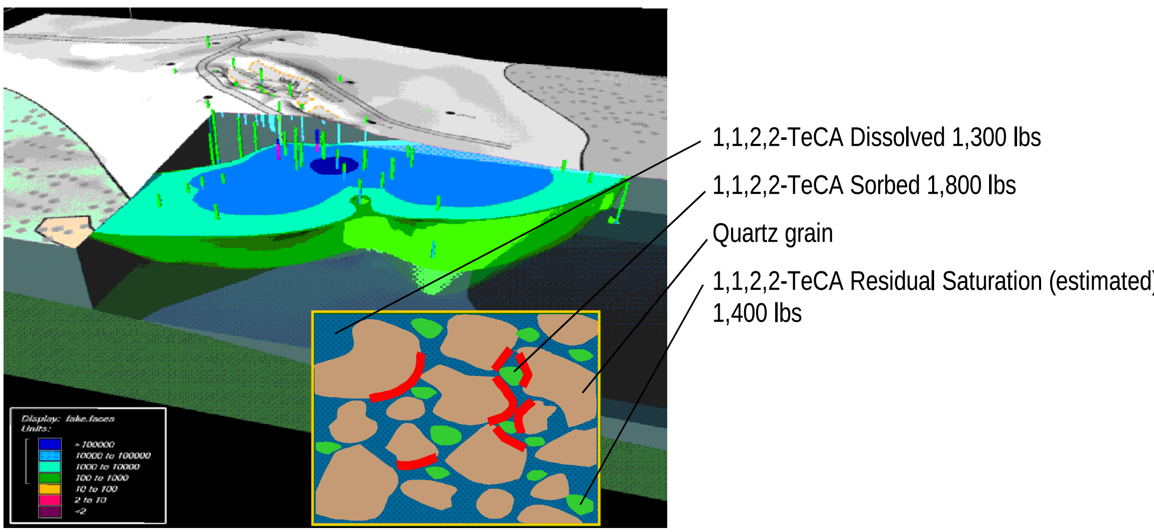


Figure 4. Three-dimensional distribution of 1,1,2,2-TeCA (μg/L)

(Hirsh, 2002)

While some assumptions were made to distinguish the different remediation technologies in the model, the results show plume capture and hydraulic influence occurring at depths up to 16 ft. MODFLOW-RT3D calculated low contaminant mass removal rates for traditional remediation techniques, but demonstrates that poplar trees have the potential to remove up to 360 lbs per year of VOCs after 30 year's time.

Dense non-aqueous phase liquid (DNAPL) was recently discovered under the Toxic Burning Pits at J-Field. The presence of DNAPL, which is being addressed under a separate project, means that groundwater VOC content will remain relatively constant. Clean-up will not occur until the location of the DNAPL is determined, remedial actions are implemented, and the contaminant source(s) are isolated or removed.

PERFORMANCE TO DATE

Groundwater flows radially from underneath the former toxic burning pits (where military weapons testing and disposal practices led to concentrated chemical release) to discharge in the freshwater marsh. Water table elevation is highest in winter, and fluctuates diurnally in the summer due to evapotranspiration. The summer growing season also yields an upward hydraulic gradient (visible up to 25 feet below the ground surface), as the tree roots increase their groundwater intake. The increased transpiration rates of the poplar trees and adjacent native woodlands cause a cone of depression to form under the poplars and in the center of the plantation. As Figure 5 demonstrates, this depression causes a reversal of groundwater flow into the plantation in the summertime, rather than outwards to the marsh.

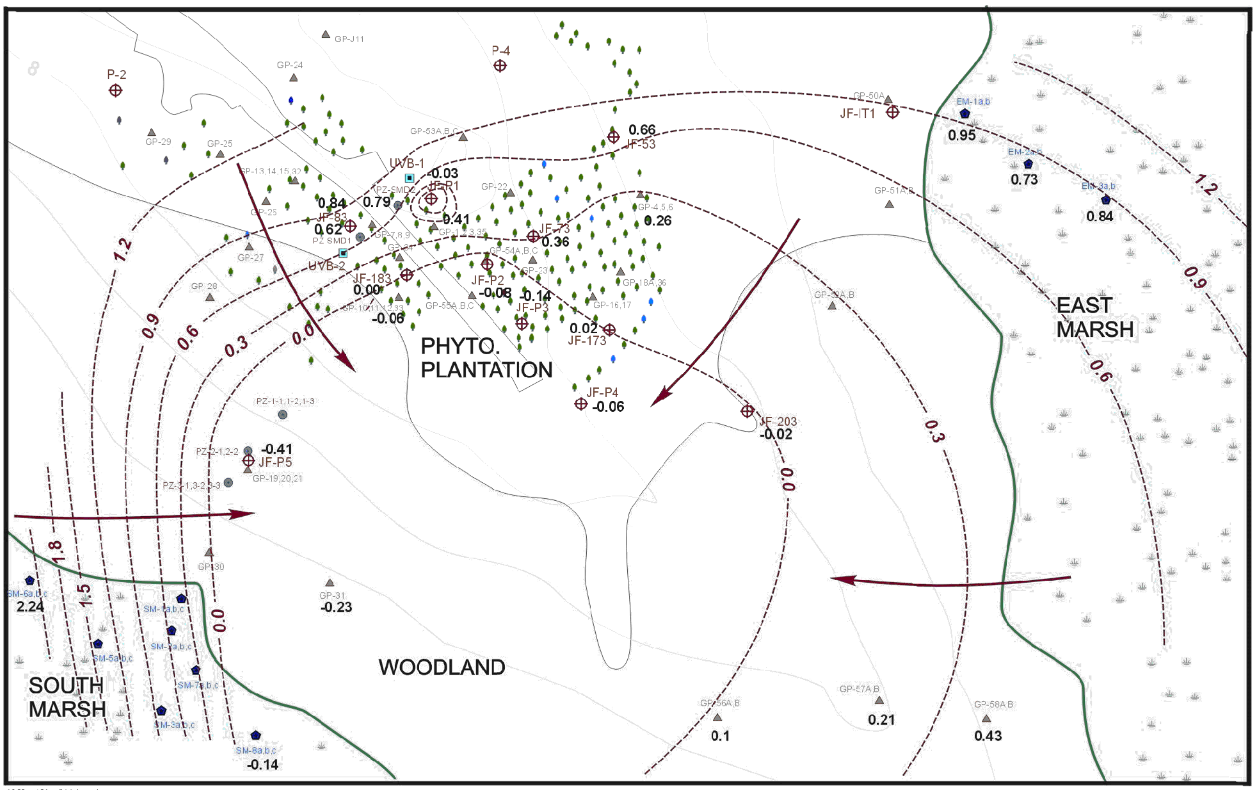


Figure 5. September 2001 Water Table Map (Schneider, 2002)

Transpiration rates for trees have been estimated using sap flow analysis and local weather (temperature, humidity, wind speed, and solar radiation) data. Results indicate that it will take 10 to15 years to achieve maximum transpiration rates of 2000 gallons per day. The leaf area index method was also used as a means of predicting the time of canopy closure, which coincides with the peak transpiration rate. This method approximated three to six more years to attain almost complete canopy closure. Further volatilization research revealed that leaves do not transpire the bulk of the contaminants. Finally, the degree of volatilization of harmful gases from the trees was found to be minimal.

Results thus far show evidence of biotic and abiotic degradation. Groundwater monitoring has revealed lower concentrations of VOCs in the flow path. It is hypothesized that the trees are also enhancing in situ biodegradation of the contaminants, an idea that is supported by the presence of vinyl chloride and ethane secondary compounds. The redox conditions of the groundwater in general are conducive to the reductive dechlorination of TCE.

The reduction of VOCs by the trees is primarily due to three mechanisms: phytodegradation, phytovolatilization, and rhizodegradation. These processes have resulted in breakdown products that are left in the vacuoles or incorporated into the tissue of the trees. After trying solvent extraction techniques to analyze tree VOC content, scientists at J-Field settled on core sampling methods to evaluate the correlation between the levels of VOCs in trees and their distribution in groundwater. Overall, the data showed a rough association between high and low points in concentration. Also, VOC content in trees decreased as samples were taken higher up the trunk and from the leaves. This has been attributed to diffusion through the tree trunk as well as transpiration through the leaves.

REFERENCES

Burken, J. and X. Ma. 2002. "Chlorinated Solvents Phytoremedation: Uptake and Diffusion." Proceedings of the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Battelle Press, Columbus, Ohio. (In Press).

Hirsh, Steven. U. S. Environmental Protection Agency. Personal Communication, July 18, 2002.

Hirsh, S., Compton, H., Haroski, H., Wrobel, J., and W. Schneider. 2003. "Five-Year Pilot Study: Aberdeen Proving Ground, Maryland." In: S. McCutcheon and J. Schnoor (eds.) *Phytoremediation: Transformation and Control of Contaminants*. John Wiley and Sons, Inc. (In Press).

Hirsh, S., Burken, J., Compton, H., Schneider, W., and J. Wrobel. 2002. "Characterizing the Remedial Performance of a Phytoremediation Pilot Study: A Case Study from J-Field, Aberdeen Proving Ground, Maryland." Battelle Remediation of Chlorinated and Recalcitrant Compounds Conference Presentation, May 21, Monterey, California.

Schneider, W.,Wrobel, J., Hirsh, S., Compton, H., and D. Haroski. 2000. "The Influence of an Integrated Remedial System on Groundwater Hydrology." In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) *Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds*, pp. 477-481. Battelle Press, Columbus, Ohio.

Schneider, W., Hirsh, S., Compton, H., Burgess, A., and J. Wrobel. 2002. "Analysis of Hydrologic Data to Evaluation Phytoremediation System Performance." Battelle Press, Columbus, Ohio. (In Press).

U.S. Environmental Protection Agency. 2002. North Atlantic Treaty Organization (NATO) / Committee on the Challenges of Modern Society (CCMS) Pilot Study: Evaluation of

Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III), 2001 Annual Report. EPA 542-R-02-001

Carswell Naval Air Station, Fort Worth, Texas

SITE DESCRIPTION

The Carswell phytoremediation demonstration project was initiated in 1996 to serve two objectives: 1) testing the ability of phytoremediation to enhance the bioremediation and phyto-degradation of chlorinated ethenes from a shallow aquifer, and 2) attaining hydraulic control of the contaminant plume. In addition to the objectives of hydraulic control and bioremediation enhancement, scientists at this site have several secondary objectives which include: evaluation of microbial contribution to reductive dechlorination; analysis of tree transpiration rates to determine water usage; and measuring of plant uptake, growth rates, and root biomass.

The site is located about one mile from the main assembly building at Air Force Plant 4, the suspected source of contamination. Plant 4 is on the National Priorities List (NPL) and the phytoremediation project is a Superfund Innovative Technology Evaluation (SITE) project. In operation since 1942, the manufacturing processes at Plant 4 currently produce F-16 aircraft, radar units, and other aircraft and missile parts. It is speculated that over the course of time, several million tons of waste solvents, oils, and fuels leaked through the ground and entered the groundwater aquifer. The TCE plume currently seems to be migrating south, with some fingers moving east.

There were several indicators that phytoremediation would be a successful choice of technology for Carswell. The aquifer at the site ranged from 6 to 11 feet below the surface, was approximately 2.3 to 4.5 feet thick, with a 2.25 percent gradient. When the project was initiated, TCE concentrations were 230 µg/L to 970 µg/L, and cis-1,2-DCE concentrations ranged from 24 µg/L to 131 µg/L. The aquifer was well oxygenated, and therefore no significant reductive chlorination had occurred.

Figure 6. Potted trees before planting (Rock, 2002)

In April 1996, about 660 cottonwood (*Populus deltoides*) trees were planted in trenches on an approximately 0.5 acre area in two rectangular plots, a whip plantation (440 trees planted 4 feet apart) and a five-gallon potted tree plantation (224 trees planted 8 feet apart). Cottonwood trees were chosen for this project because of their quick and extensive root growth, rate of evapotranspiration, and suitability to the environmental conditions at the site (Figure 6).

Using this information along with the hydraulic conductivity and aquifer porosity, the aquifer volume and flow were calculated to be 550,000 gal and 2,800 gpd respectively. The planting density was then determined based on the maximum transpiration rates of the trees (26 gpd). The plantations were irrigated by drip system for the first two growing seasons to promote deep root development.

PERFORMANCE TO DATE

Percent change in mass of TCE measured in the downgradient portion of the site was used to determine whether phytoremediation was reducing contaminant levels. The available data (through 1999) seem to indicate that this objective may be achieved through hydraulic control. The volumetric flux decreased by 8 percent in the third growing season (1999), resulting in about 106 gpd less water moving toward the downgradient part of the site than in 1996. TCE concentrations in the downgradient wells did not decrease, however (469 g/L in 1996 compared to 473 g/L in 1999). Since 1999, data collected from these wells could no longer be used to map drawdown, because the cone of influence of the planted trees has since expanded to encompass the formerly downgradient location of the wells. Groundwater contaminant concentration data from 2000 and 2001 will be published in a journal article in the near future.

Groundwater flow modeling with MODFLOW predicted a decrease in volumetric flux of groundwater across the downgradient end of the plantation of 20 to 30 percent, due to transpiration rates of 1,000 to 1,900 gpd during peak growing seasons. The model is assumed to be fairly well-calibrated, because when transpiration rates for 1998 were entered into the system, it estimated drawdown at the center of the cone of influence to be 0.295 ft, closely matching the observed drawdown of the water table of 0.328 ft in that year. Assuming that assumptions about climatic conditions are correct and that TCE concentrations remain the same, mass flux is expected to decrease by about 15 to 22 percent (74 percent of the volumetric flux). Model results indicate no hydraulic control of the TCE plume during the dormant season.

Analyses of the concentrations of dissolved oxygen (DO), dissolved iron, molecular hydrogen, methane, and dissolved organic compounds signify that anaerobic conditions favoring reductive dechlorination are developing. Results of data from January 2001 show dissolved oxygen concentrations of less than 1 mg/L from several wells located beneath the trees. This concentration is much lower than DO levels upgradient of the site, which had an average concentration of above 4.5 mg/L. Ratios of TCE to cis-DCE were as low as 2.5 in groundwater downgradient of the planted area, compared to ratios of 5.0 for upgradient samples (Figure 7). In addition, a microbial study conducted by USGS showed that numbers of anaerobes and methanogens were generally higher in planted, contaminated areas than in control areas. When the data are viewed from a historical perspective, they support the researchers' conclusion that the groundwater has been (and may continue to be) in a state of geochemical transition for several years after planting.

Another area of research at the Carswell site involved comparing the maximum transpiration rates for the whips and potted trees. Sap flow data for both plantations was the highest in June, and the lowest in October. However, the July 2000 sap flow rate for the potted trees was about quadruple that of the whips (80 kg/tree/day compared to 20 kg/tree/day respectively).

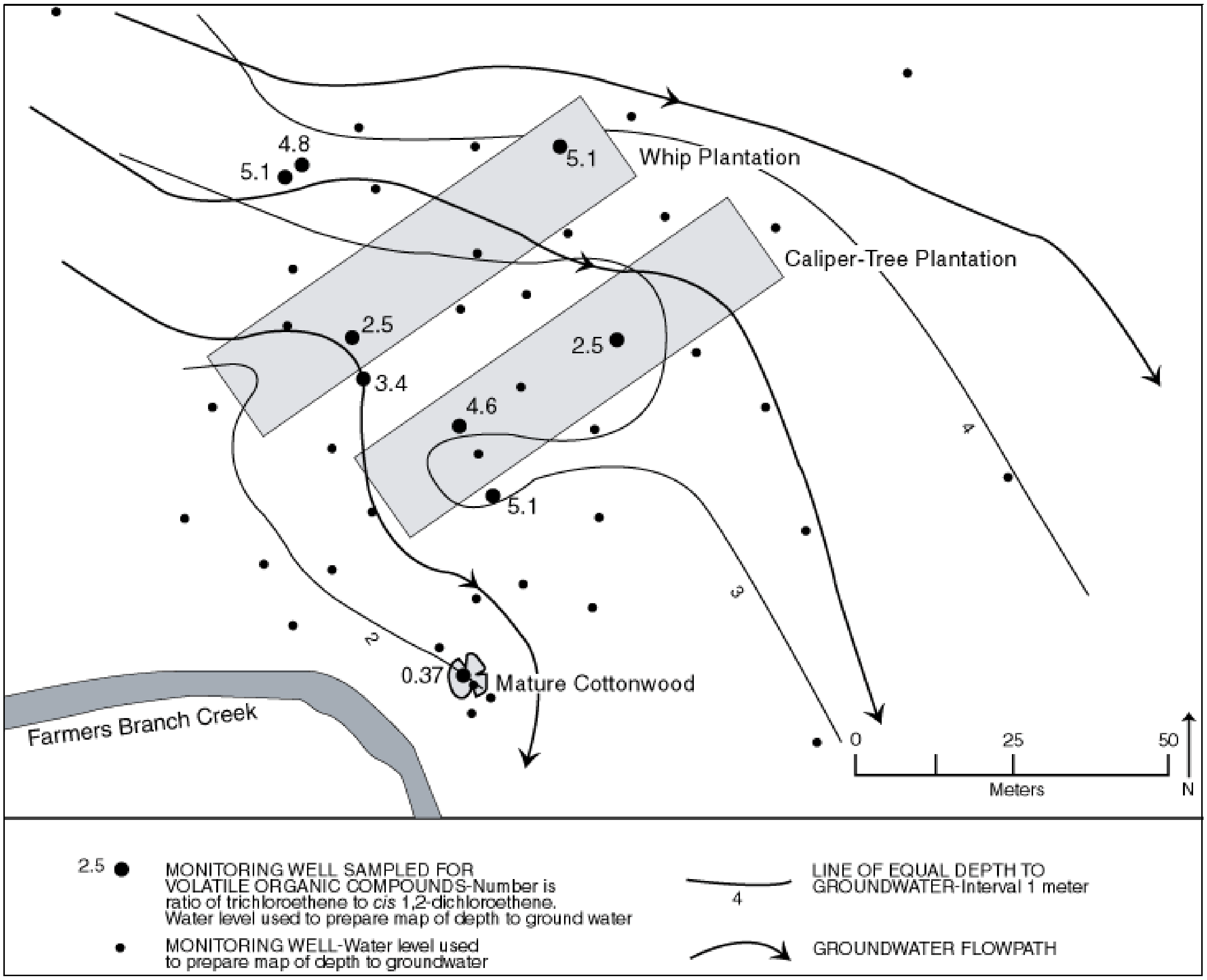


Figure 7. The layout of the Carswell phytoremediation site, TCE/DCE ratio, depth to groundwater, and groundwater flowpaths in September 2000 (Eberts, 2002)

To establish the level of contaminant uptake in the plants, root, stem, and leaf samples were taken and analyzed for VOCs. Most of the trees that were sampled contained TCE and cis-DCE. TCE and DCE concentrations were generally higher in the stem than the leaf samples. Transpired vapors were not sampled and analyzed from trees at this site.

Based on the data gathered, scientists determined that stem samples had the greatest diversity and concentration of chlorinated compounds. As expected, they also found that the concentration of contaminants and the number of trees with detected contaminants increased over time. The whips and the potted trees had similar levels of contaminant concentration (32 µg/kg and 24 µg/kg of TCE in respective tree stems). The fate of these contaminants within the plants is currently still unclear. This subject will be addressed in more detail in the Discussion section of this paper.

Trees grew well and were healthy for the most part of the study. There was a 5 percent mortality rate among trees, mostly due to damage from monitoring efforts. Trunk diameters expanded from 1.41 cm to 5.13 cm for the whips, and 3.83 to 8.12 cm for the potted trees. Tree height also increased from 7.45 feet to 18.12 feet for the whips and 12.38 feet to 21.78 feet for the potted trees. Root biomass was slightly higher for the potted trees, and roots of all trees reached deep enough to access groundwater. With trees planted 4 feet apart, the whip plantation was approaching canopy closure in 1998. In the potted tree plantation, on the other hand, the trees were spaced 8 feet apart at planting and were not yet near canopy closure. By the 2000 growing season, however, the situation had changed. The trees in the potted tree plantation were nearer to canopy closure than those in the other plantation. This difference led the potted trees to outperform the whips in transpiration rate, and seems to indicate that the additional expense of planting potted trees may be worthwhile.

Lastly, a 19-year-old cottonwood tree on site was monitored to estimate the potential of phyto-remediation by mature cottonwoods. There was a high amount of microbial activity in the groundwater underneath the tree, reflecting the likelihood of reductive dechlorination. Sap flow rates for the tree have been estimated to be as high as 280 kg/day. While it is unlikely that trees in the plantation will achieve this rate of transpiration, the initial analysis of the data gathered from this tree seems promising.

Future plans for this site are not clear; at a minimum, semi-annual sampling will continue. USGS models of the site indicate that maximum transpiration will occur around 2007, and will cause a drawdown of 0.65 feet at the center of the site.

REFERENCES

Eberts, S., Harvey, G., Jones, S., and S. Beckman. 2003. "Multiple Process Assessment for a Chlorinated-Solvent Plume." In: S. McCutcheon and J. Schnoor (eds.) *Phytoremediation: Transformation and Control of Contaminants*. John Wiley and Sons, Inc. (In Press).

Lee, R., Jones S., Kuniansky, E., Harvey, G., Lollar, B., and G. Slater. 2000. Phreatophyte Influence on Reductive Dechlorination in a Shallow Aquifer Contaminated with Trichloroethylene (TCE). International Journal of Phytoremediation, 2 (3): 193-211.

Rock, Steven. U. S. Environmental Protection Agency. Personal Communication, July 31, 2002.

Rock, S., and G. Harvey. 2002. Innovative Technology Evaluation Report. (Draft)

U.S. Environmental Protection Agency. 2002. North Atlantic Treaty Organization (NATO) Committee on the Challenges of Modern Society (CCMS) Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III), 2001 Annual Report. EPA 542-R-02-001.

Edward Sears Property, New Gretna, New Jersey

SITE DESCRIPTION

Toxic materials such as paints and adhesives were stored in leaky drums on Edward Sears' property for decades. The soil and groundwater at the site were consequently contaminated with dichloromethane (up to 490,000 ppb), PCE (up to 160 ppb), TCE (up to 390 ppb), trimethylbenzene (TMB, up to 2,000 ppb), and xylenes (up to 2,700 ppb). Depth to the aquifer at this site is about 9 feet, and most of the contamination is located between 5 and 18 feet below the surface. The soil at this site is a loamy sand and is slightly acidic.

In December of 1996, 118 hybrid poplar trees (*P. charkoweiiensis x incrassata*, NE 308) were planted on about 0.33 acres as part of a pilot-scale phytoremediation project implemented by the EPA's Environmental Response Team. Using a deep-rooting planting process to maximize groundwater uptake, 12-foot trees were planted 9 feet under the ground, with only 2 to 3 feet remaining above the surface. Trees were planted about 10 feet apart.

Fertilizer has been applied to trees annually at rates based on soil fertility results in order to promote tree growth. Pesticides were also used to prevent various problems that have been encountered in the past such as caterpillars that defoliate trees.

PERFORMANCE TO DATE

During the 1998 growing season, large reductions in dichloromethane and trimethylbenzene were reported. The reductions were sustained through 2001, with the highest TCE concentration of 87 µg/L found in well WP12 in August 2001. This reflects a decrease of over 80 percent from the initial concentration of 500 µg/L in 1995. The highest DCM and TMB concentrations found in the 2001 sampling were 2 µg/L and 500 µg/L, respectively. Methylene chloride, which was once present at concentrations greater than 5,000 µg/L, is now virtually non-detectable. The only two contaminants that have not shown much reduction are xylene (at a maximum concentration of 3,000 µg/L in 2001) and PCE (Figure 8).

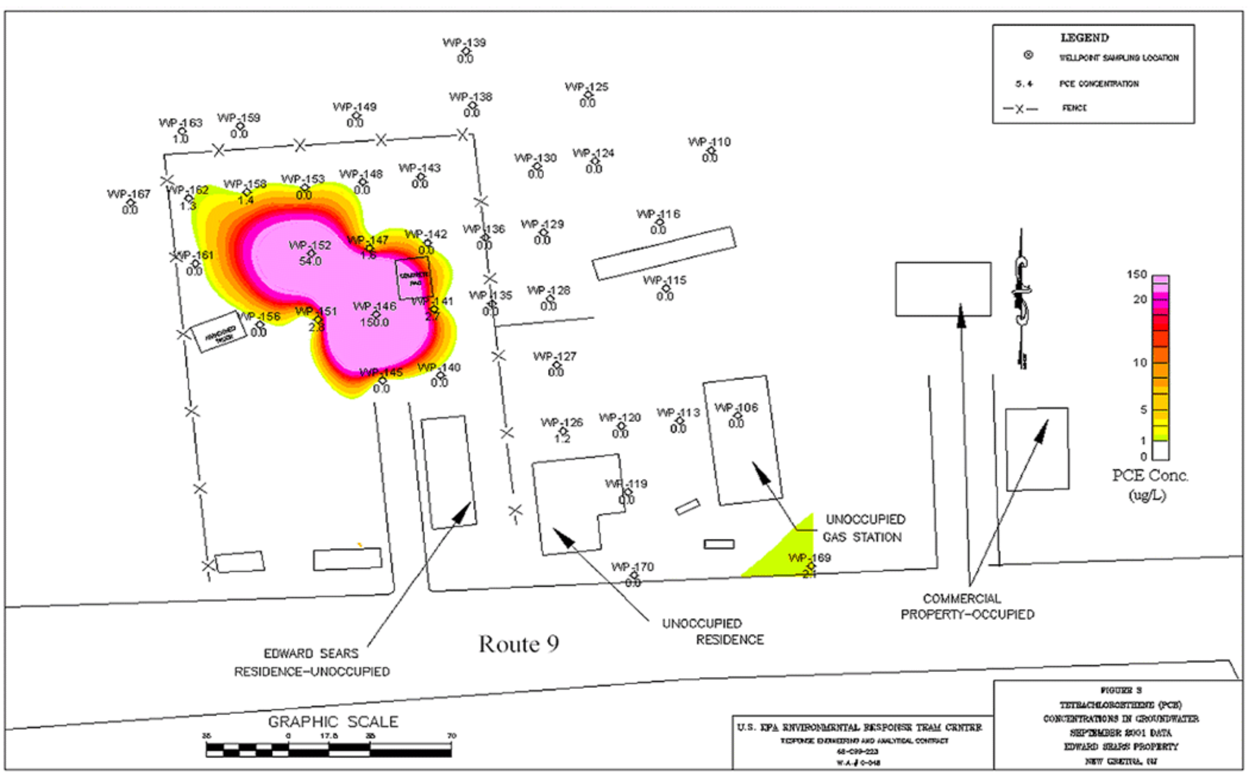


Figure 8. PCE concentrations in groundwater at Edward Sears Property, September 2001 (Gussman, 2002)

Hydraulic control is not measurable at this site because of the tidal water table and sandy soil conditions with high hydraulic conductivity. Groundwater flows east towards Job's Creek (located about 0.25 miles away).

Initially, trees were not reaching their expected height and diameter in the areas of high VOC contamination. Since the second growing season, however, this observation seems to be less pronounced. While the trees growing in the contaminated area are still not as tall or thick as their counterparts in other areas, they are still growing fairly rapidly.

Based on 2001 sap flow data, the trees are removing about 352 gpd of water (or 3.08 gpd per tree) during the summer season. In 1998, evapotranspiration measurements detected only low levels of toluene (8 to 11 ppb). In 2001, no VOCs of interest were found in the transpiration gas samples collected by placing Tedlar bags over several trees.

Transpiration testing for this site may become more extensive in the future, because results as yet are inconclusive. Groundwater sampling and tree monitoring will continue on a semi-annual basis.

REFERENCES

Gussman, C. 2001. August 2000 Field Activities, Edward Sears Site, New Gretna, New Jersey, Work Assignment 0-048 – Trip Report. Lockheed Martin Technology Services, Edison, New Jersey.

Gussman, C. 2002. Field Activities 2001, Edward Sears Property, New Gretna, New Jersey, Work Assignment 0-048- Status Report. Lockheed Martin Technology Services, Edison, New Jersey.

Gussman, Christopher. Lockheed Martin. Personal Communication. October 4, 2002.

Mohn, M. 1997. Groundwater, Soil Gas, and Plant Gas Sampling Activities, Edward Sears Site, Work Assignment 2-120-Trip Report. Roy F. Weston, Edison, New Jersey.

U.S. Environmental Protection Agency, Environmental Response Team. 1997. Final Report, Hydrogeological Investigation, Edward Sears Site, New Gretna, New Jersey.

U.S. Environmental Protection Agency. 2002. North Atlantic Treaty Organization (NATO) / Committee on the Challenges of Modern Society (CCMS) Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III), 2001 Annual Report. EPA 542-R-02-001.

Kauffman & Minteer, Jobstown, New Jersey

SITE DESCRIPTION

This is a five-acre Superfund site consisting of a garage/office building, a former truck washing area, a former collection pit area, a drainage ditch, and a former unlined lagoon. From 1960 to

1980, Kauffman & Minteer, Inc transported bulk liquids such as synthetic organics, plasticizers, resins, oils, and alcohols from this location in Jobstown, New Jersey. The company discharged toxic wastewater from cleaning its trucks into the drainage ditch and unlined lagoon. In June of 1984, the dike surrounding the lagoon collapsed, sending 13,000 m^3 of wastewater into a nearby wetland. Discharge from the lagoon and washing area has contaminated the shallow groundwater at the site, and threaten the Wenonah-Mount Laurel aquifer, a source of drinking water for the community.

Phytoremediation has been selected as part of a long-term groundwater remedial strategy. In March of 1998, 75 hybrid poplar (*P. maximowiczii x trichocarpa*) and native black willow (*Salix nigra*) were planted in the former lagoon and drainage ditch areas. The objectives of this pilot-scale phytoremediation study are: 1) to examine the capacity of the trees to mitigate shallow soil and groundwater contamination at the planting sites, and 2) to prevent migration of the contaminant plume through hydraulic control.

In the fall of 1998, 132 new and 46 replacement poplar and willow trees were added to the study. In the spring of 1999, 58 more trees were planted in the former truck wash bay area.

The Kauffman & Minteer site is located on the Mount Laurel Sand/Wenonah Formation of the Upper Cretaceous Age. This Formation is an approximately 60 feet thick, unconfined aquifer. The first layer of Mount Laurel sand is about 20 feet thick and consists of silty sand and clays, while the second Wenonah layer, about 40 feet thick, consists of silty micaceous quartz sand. At 60 feet below ground surface, the Marshalltown Formation serves to confine the Mount Laurel Sand/ Wenonah Formation and separate it from the Englishtown Formation at 90 feet below ground surface.

Depth to groundwater at the site ranges from 6.32 feet to 15.95 feet. A groundwater contaminant plume containing primarily cis-1,2-DCE and TCE originates under the former truck wash bay and drainage ditch and migrates south-southwest in the direction of groundwater flow. A hydrogeological investigation and aquifer pumping test were conducted to obtain some basic data on the aquifer. This information has been used in a two-dimensional model of the shallow aquifer, which helped to determine the predominant groundwater flow direction, the hydraulic conductivity (7.5-11.5 ft/day), and the fact that the former lagoon and wetland seem to provide recharge to the site.

PERFORMANCE TO DATE

It is too early to assess the success of phytoremediation at this site. According to data gathered in November 2001, eight out of 21 sampled wells actually exhibited an increase in TCE, cis-1,2-DCE, and vinyl chloride concentrations since initial measurements were made in April 1998 and September 1999. It is speculated that this may be due to soil excavation and backfilling at the drainage ditch and former truck wash area, which changed the natural hydrogeologic conditions of the site to a higher porosity material (sand).

Transpiration gas samples taken in June 2001 did not detect any significant amounts of TCE, trans-1,2,-DCE, or styrene. Sap flow measurements made in August of the same year indicated that there is a significant amount of water uptake by the trees.

According to maintenance performed in June 2001, the trees are growing well and in good health. There were some problems with moth larvae found on poplars, and caterpillars feeding on willow trees. The trees were mulched and Miracle-Gro fertilizer spikes (15N:10P:9K) were installed adjacent to all trees.

No specific measures of rhizodegradation were made at this site. This, as well as more extensive contaminant source investigations, may be areas of future research.

REFERENCES

Chu, C., Woodruff, K., and C. Gussman. 2001. June to October 2001 Groundwater Sampling Event, Pump Test, Geophysical Survey, and Pilot-Scale Phytoremediation Study Monitoring and Maintenance Activities, Kauffman & Minteer Site, Jobstown, New Jersey, REAC Work Assignment No. R1A00041 – Technical Memorandum. Lockheed Martin Technology Services, Edison, New Jersey.

Prince, George. U. S. Environmental Protection Agency. Personal Communication, August 23, 2002.

Vernal Naples Truck Stop, Vernal, Utah

SITE DESCRIPTION

The Vernal Naples Truck Stop phytoremediation site is an example of the intended use of phytoremediation as a polishing step to clean up remaining contaminants after a faster, more conventional technology has sufficiently reduced contaminant levels. From 1994 to 1998, the site was remediated by vacuum-enhanced pumping/biotreatment, thermal oxidation, and granular activated carbon filtration.

In 1998, managers of this site adopted a long-term approach to remediation at this site. Approximately 300 Sioux-land poplar trees were planted down and cross-gradient of the gasoline and MTBE plume.

PERFORMANCE TO DATE

During the summer of 2000, 25 percent of the trees died and 35 percent were highly stressed. This may have been due to insecticide spraying, or a lack of irrigation. The dead trees were replaced with 50 more Sioux-land poplar trees in the summer of 2001.

Gasoline concentrations in groundwater show a slow decrease on one well since 1998, and pending the results of the next sampling event, may be decreasing in other wells. The maximum gasoline concentration in June 2001 was 9 mg/L. MTBE groundwater concentrations recorded in June 2001 are the highest to date (an increase from 720 mg/L in 2000 to 750 mg/L in 2001). At the time of writing this report, no data from the 2002 monitoring activities were available.

There may be a difference in the distribution of MTBE and gasoline. It was speculated in 2000 that, because MTBE is more soluble in water, the MTBE plume may have moved downgradient and off-site at a faster rate than the gasoline plume. Groundwater elevation contours do not indicate hydraulic effects from the trees. To date, there have not been any detectable chemical or hydraulic effects resulting from the phytoremediation system at this site.

REFERENCES

Griswold, Hays. September 28, 2000. U.S. Environmental Protection Agency Pollution Report.

Griswold, Hays. January 11, 2001. U.S. Environmental Protection Agency Pollution Report.

Griswold, Hays. August 15, 2001. U.S. Environmental Protection Agency Pollution Report.

Tibbetts Road, Barrington, New Hampshire

SITE DESCRIPTION

The Tibbetts Road Superfund site is a two-acre site that was once used for the storage of drums containing thinners, solvents, antifreeze, kerosene, motor oil, polychlorinated biphenyls (PCBs), grease, and brake fluid. EPA has been working on the site since 1984, removing drums, excavating contaminated soil, and pumping and treating the contaminated groundwater.

About 1,400 hybrid poplars (one-year-old rooted *P. deltoides x nigra*) were planted in 1998 as a final polishing step after several years of active treatment at the site using vacuum extraction. Phytoremediation was chosen for the site primarily as a means of providing hydraulic control of the remaining groundwater contaminant plume in lieu of pump and treat. EPA was also interested in determining whether naturally-occurring degradative processes could be enhanced through the use of phytoremediation.

PERFORMANCE TO DATE

Results from the 2001 Summary of Environmental Monitoring showed that groundwater flows radially away from a topographic high point near the center of the site. The 2001 Summary report also states that, despite significant seasonal and yearly variability, there is a general downward trend in the concentrations of VOCs in groundwater at the site.

Overall, water levels in overburden aquifer decreased based on 2001 data (about 3 to 5 ft). However, due to the topography and hydrology of the site, no cone of depression has been observed. The specific impacts of the phytoremediation system on the overall groundwater hydrology are not yet clear.

Tibbetts Road will undergo a five-year review next year, when future plans for the site will be determined. More monitoring wells may be installed in order to assess plume movement.

REFERENCES

Arcadis, Geraghty, & Miller, Inc. 1998. Phytoremediation Installation Report Tibbetts Road Site, Barrington, New Hampshire.

Arcadis, Geraghty, & Miller, Inc. 2002. Summary of Environmental Monitoring 2001, Tibbetts Road Site, Barrington, New Hampshire.

Handler, Neil. U. S. Environmental Protection Agency. Personal Communication, August 19, 2002.

U.S. Environmental Protection Agency, Region I. 1998. Amended Record of Decision, Tibbetts Road Superfund Site, Barrington, New Hampshire.

Former Chevron Light Petroleum Products Terminal, Ogden, Utah

SITE DESCRIPTION

From the 1950s until 1989, Chevron stored and transferred petroleum products on this five-acre facility. Groundwater at this site is about six feet below the surface, and is contaminated with BTEX and other petroleum hydrocarbons at concentrations of 5 to 10,000 ppb.

In 1996, under the auspices of the EPA's SITE demonstration program, 40 poplar trees (*P. deltoides x nigra*) were planted as "poles" in boreholes. The rows of trees were installed perpendicular to the direction of groundwater flow.

PERFORMANCE TO DATE

Although transpiration rates for the entire stand were estimated at about 445 gpd (1999), no zone of depression was observed under the trees. However, as of 2000, a decrease in both BTEX and petroleum hydrocarbon concentrations had been observed.

There is no recent groundwater contaminant concentration data available on this site, since monitoring activity has ceased. The plantation is still being maintained.

REFERENCES

Ferro, A., Kjelgren, R., Turner, D., Chard, B., Montague, T., and J. Chard. 2000. “Phytoremediation Systems Designed to Control Contaminant Migration.” In: EPA Phytoremediation: State of the Science Conference Proceedings, Boston, MA, May 1-2, 2000.

Ferro, A., Chard, J., Kjelgren, R., Chard, B., Turner, D., and T. Montague. 2001. “Groundwater Capture Using Hybrid Poplar Trees: Evaluation of a System in Ogden, Utah.” International Journal of Phytoremediation. 3(1): 87-104.

Zollinger, Nickolee. Phytokinetics, Inc. Personal Communication. August 19, 2002.

Solvent Recovery Services of New England (SRSNE), Southington, Connecticut

SITE DESCRIPTION

The contaminant source at this Superfund site is a DNAPL containing primarily TCE, PCE and toluene in both the overburdened and bedrock aquifers. Currently, contaminated groundwater at this site is pumped from an overburden aquifer, treated with UV oxidation, and discharged to the Quinnipiac River. Containment is also provided by a downgradient sheet pile wall. A dense stand of 1,000 hybrid poplars (*P. deltoides x nigra*) was planted in 1998. If the phytoremediation system can be shown to reduce groundwater migration and remove aqueous-phase VOCs, it will reduce the volume of contaminated water that needs to be collected and treated on site.

PERFORMANCE TO DATE

There was a 40 percent mortality rate for the trees planted in 1998. As a result, willows and native tree species were added in 1999 to replace the trees that died. In spring 2002, all of the poplar trees were removed from the site due to a canker problem. The stand is currently made up of approximately 380 willows and 37 native trees.

June to September 2001 sap flow measurements indicated water use rates of 7.8 gpd for willows and 8.4 gpd for poplars. At the time of writing this report, there was no groundwater concentration data available.

REFERENCES

Ferro, A., Kennedy, J., Kjelgren, R., Rieder, J., and S. Perrin. 1999. “Toxicity Assessment of Volatile Organic Compounds in Poplar Trees.” International Journal of Phytoremediation. 1(1): 9-17.

Ferro, A., Chard, B., Gefell, M., Thompson, B., and R. Kjelgren. 2000. “Phytoremediation of Organic Solvents in Groundwater: Pilot Study at a Superfund Site.” In: G. Wickramanayake,

A. Gavaskar, B. Alleman, and V. Magar (eds.) Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds, p461-466. Battelle Press, Columbus, Ohio.

Lumino, Karen. Environmental Protection Agency. Personal Communication. August 26, 2002.

Phytokinetics, Inc. Phytoremediation Pilot Study at the Solvent Recovery Services of New England (SRSNE) Superfund Site: 1998 Report for the Field-Scale Installation. North Logan, Utah.

Phytokinetics, Inc. Phytoremediation Pilot Study at the Solvent Recovery Services of New England (SRSNE) Superfund Site: 1999 Progress Report and 2000 Work Plan. North Logan, Utah.

Phytokinetics, Inc. Report of Field Work 2001 and Proposal for 2002. North Logan, Utah.

Phytokinetics, Inc. Sap Flow Measurements at the SRSNE Superfund Site, Southington, CT: Report of Field Work 2000 and Proposal for 2001. North Logan, Utah.

U.S. Environmental Protection Agency. 1997. “Pump and Treat of Contaminated Groundwater with Containment Wall at the Solvent Recovery Services of New England, Inc. Superfund Site Southington, Connecticut.” Federal Remediation Technologies Roundtable Remediation Case Study, http://costperformance.org/html/00000136.html.

Zollinger, Nickolee. Phytokinetics, Inc. Personal Communication. August 26, 2002.

Discussion

The purpose of this report was to assess phytoremediation performance in terms of hydraulic plume control. It was not possible to collect all data on all relevant projects in the three months taken to compile this report; however the conclusions below can safely be made.

There is a need for more published information on system performance and lessons learned from phytoremediation sites, especially those that have been in progress for more than four years. Due to the inaccessibility of comprehensive data (site hydrogeology, topography, etc.) from the majority of these sites, it was not possible to compare results between sites in much detail in this report.

Historical groundwater contaminant concentration data, necessary to assess the degree of hydraulic control achieved at each site, was a key piece of information lacking at several sites. Instead, many reports emphasized contaminant mass removal, which is a function of the volume of groundwater taken up by the trees. Because the goal of plume capture is the elimination of contaminants in downgradient groundwater, contaminant mass removal estimates should always be accompanied by groundwater contaminant concentration measurements.

Objectives

While complete plume capture via phytoremediation is theoretically possible, the results to date show that it is not likely. At Carswell Naval Air Station, for example, the estimated decrease in volumetric flux of groundwater at maximum transpiration rates for about 660 cottonwoods was only 20 to 30 percent. This result suggests that reduced transport of contaminants may be a more realistic goal, especially for areas that are inaccessible to the public.

Although the other case studies presented in this paper are between four and six years old, it was difficult to identify specific contaminant reduction trends among varying compounds and their concentrations up and down-gradient of the tree stands. At the Edward Sears Property site, for example, researchers pointed out a general decrease in TCE and trimethylbenzene, while the levels of PCE and xylenes remain inexplicably high. At the Kauffman & Minteer site, the contaminant levels in one-third of the groundwater wells actually increased.

Technology Evaluation

There are still many questions concerning phytoremediation mechanisms, such as rhizodegradation, hydraulic influence, and the volatilization of contaminants. For example, extensive research on rhizodegradation was conducted at the Carswell site. However, several key issues still remain unresolved. It is still not clear whether complete degradation can be achieved via rhizodegradation, and exactly how the mechanisms involved are enhanced by the presence of plants. Sites other than Carswell did not seem to be studying rhizodegradation in great detail. Due to the site-specificity of phytoremediation, rhizodegradation should be explored at several sites to determine its potential.

In addition, the presence and hydrologic effects of cones of depression was not discussed in most site-specific annual reports. At Aberdeen Proving Ground, the cone of depression formed underneath the poplar plantation resulted in a reversal of groundwater flow during summer months. At the Tibbetts Road site, on the other hand, it is not yet clear how a topographic high point affects site hydrology and plume movement.

Most phytoremediation sites had extensive data from sap flow measurements, made accessible through annual reports and papers. However, as mentioned above, while groundwater uptake via transpiration is an indicator of contaminant uptake, it is only an indirect measure of hydraulic control and no substitute for groundwater contaminant sampling to determine the extent of plume control. Also, many studies did not distinguish between what portion of tree water uptake is from the groundwater or from soil near the surface (precipitation). This type of analysis can be done by measuring the molar ratios of the stable isotopes of hydrogen (hydrogen and deuterium).[16] A convincing analysis of phytoremediation at any site should consider this distinction.

Another consideration in assessing the efficacy of phytoremediation is the other technologies with which it has been used. For example, soil excavation and backfilling may have affected the hydrogeology of the Kauffman & Minteer phytoremediation site, which in turn may have altered the spread of the contaminant plume. Phytoremediation is often used in conjunction with monitored natural attenuation (MNA) at the end of a treatment train of other remediation technologies, in particular as a polishing step after "pump and treat." Given the information available today, no firm assessments can be made regarding the effectiveness of phytoremediation-attributed contaminant removal versus MNA at the same site. Further research into this subject area is necessary to evaluate the phytoremediation-MNA combination at sites such as NUWC Keyport in Washington state and the Ashland, Inc. site in Milwaukee, WI (see Appendix).

Once consistent performance data are available, a final step in the technology evaluation process will be an objective analysis of tree planting methods from site to site, taking into account differences in factors such as soil type, climate, and contaminant plume dimensions. A significant number of trees planted at the Aberdeen site were thrown over by wind due to the lack of lateral support roots. Results from several other sites, the Vernal Naples Truck Stop and SRSNE sites in particular, were affected by high mortality rates, which might have been averted with different irrigation practices and pesticide use.

Modeling Results

Almost every phytoremediation site has used modeling programs to simulate and predict groundwater contaminant flow and uptake. However, models do not take into account contaminant diffusion and degradation, and therefore do not present a comprehensive view of the effects of phytoremediation. For this reason, it will be informative to revisit projects such as Carswell in a few years, to see how model predictions compare with observed results. A better understanding of phytoremediation mechanisms, especially phytoremediation-enhanced in situ

[16] Ferro et al., 2002.

bioremediation, will help define model limitations, and lead to improved project design and optimization.

Phytovolatilization

The fate of VOC contaminants in the phytoremediation system has been unclear for a long time now. Field studies have not been able to detect high concentrations of contaminants in transpiration from leaves. In addition, tree core samples have shown that levels of contaminants decrease with increasing distance from the ground. This has led to questions about what happens to the VOCs after uptake into the plant roots and stem. One possibility is that, through phytodegradation, the VOCs are metabolized and transformed. This theory has been supported by laboratory and fieldwork conducted at the University of Washington.[17]

Recent studies at the University of Missouri-Rolla[18] may have elucidated another route of contaminant removal. Through laboratory and field tests, Burken and Ma have shown that a significant amount of VOC contaminant is released into the atmosphere from the plant stem or trunk via diffusion.

Tree core samples taken from the Aberdeen site showed a radial decrease in TCE concentration, and very little TCE in leaf tissue. Ma hypothesizes that the translocation speed of the contaminant depends on the amount of water uptake and the diameter of the tree trunk. The radial diffusion process then can be estimated according to Fick's First Law

$$t = \frac{(L/2)^2}{D}$$

where L is the radius of the tree trunk and D is the diffusion coefficient. Because the thickness of the trunk is only a fraction of the length of the trunk, it follows that the diffusion process dominates the transpiration process in the field studies.[19] Currently, the data necessary to calculate exactly what percentage of the contaminant is diffused from the trunks of trees in the field are elusive. However, once VOCs are in the atmosphere, they are susceptible to photodegradation at rates depending on the size and shape of the compound.

Challenges

Of the 55 phytoremediation projects presented in the body of this paper and Appendix, many are still in the early stages of development. One of the difficulties in assessing the effectiveness of phytoremediation is that projects must have at least three years of monitoring data for results worth reporting. Once trees are closer to attaining full root development and canopy closure, and reliable data on their effects on the contaminant concentration and migration of the plume are

[17] Gordon et al., 1998.

[18] Ma et al., 2002, and Burken et al., 2002.

[19] Ma et al., 2002.

available, the subsequent challenge for this site-specific technology will be comparison between sites.

Unlike the research sites described earlier in this paper, private firms implementing phytoremediation projects seem to view phytoremediation as a low-cost technology, which precludes extensive, long-term monitoring of the effects of many of the phytoremediation mechanisms. The Former Chevron Light Petroleum Products Terminal phytoremediation site seems to be one victim of the lack of funding for long-term projects.

Application Potential

There are many advantages to phytoremediation. For example, at both the Tibbetts Road and SRSNE sites, phytoremediation was selected because of its ability to gradually remediate the overburden aquifer without the threat of further contaminating the fractured bedrock underneath. The diversity of applications of phytoremediation, from landfills to brownfields, makes it an attractive remediation choice. But while phytoremediation may be a cheaper alternative to competing technologies, its effectiveness has still not been conclusively proven, and thus implementation of the technology is limited.

Currently the Interstate Technology and Regulatory Council (ITRC) Decision Tree Document and Research Technologies Development Forum (RTDF) database and Evaluation Protocol provide some general guidance to professionals who are considering or are already implementing phytoremediation projects, but more technical information is needed to make an informed decision on the potential efficacy of phytoremediation at a particular site. This process would be facilitated with authoritative guidelines standardizing data monitoring and reporting procedures. Comparable methods of information gathering and processing would allow for more straightforward, results-based analysis of projects with similar objectives.

While unable to reach a firm conclusion about the effectiveness of phytoremediation in the field, this report has identified several projects and documented their available results. Follow-up on these projects in the future is recommended for more insight into the functionality and effectiveness of the mechanisms involved in phytoremediation of VOC-contaminated groundwater.

Bibliography

Arcadis, Geraghty, & Miller, Inc. 1998. Phytoremediation Installation Report, Tibbetts Road Site, Barrington, New Hampshire.

Arcadis, Geraghty, & Miller, Inc. 2002. Summary of Environmental Monitoring 2001, Tibbetts Road Site, Barrington, New Hampshire.

Burken, J. and X. Ma. 2002. "Chlorinated Solvents Phytoremedation: Uptake and Diffusion." Proceedings of the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Battelle Press, Columbus, Ohio. (In Press).

Chu, C., Woodruff, K., and C. Gussman. 2001. June to October 2001 Groundwater Sampling Event, Pump Test, Geophysical Survey, and Pilot-Scale Phytoremediation Study Monitoring and Maintenance Activities, Kauffman & Minteer Site, Jobstown, New Jersey, REAC Work Assignment No. R1A00041 – Technical Memorandum. Lockheed Martin Technology Services, Edison, New Jersey.

Collins, C., Laturnus, F., and A. Nepovim. 2002. "Remediation of BTEX and Trichloroethene: Current Knowledge with Special Emphasis on Phytoremediation." Environ. Sci. & Pollut. Res. 9 (1): 86-94.

Ferro, A., Kjelgren, R., Turner, D., Chard, B., Montague, T., and J. Chard. 2000. "Phytoremediation Systems Designed to Control Contaminant Migration." In: EPA Phytoremediation: State of the Science Conference Proceedings, Boston, MA, May 1-2, 2000.

Ferro, A., Chard, J., Kjelgren, R., Chard, B., Turner, D., and T. Montague. 2001. "Groundwater Capture Using Hybrid Poplar Trees: Evaluation of a System in Ogden, Utah." International Journal of Phytoremediation. 3(1): 87-104.

Ferro, A., Gefell, M., Kjelgren, R., Lipson, D., Zollinger, N., and S. Jackson. 2002. "Maintaining Hydraulic Control Using Deep Rooted Tree Systems." In: G. Tsao and D. Tsao (eds.) *Advances in Biochemical Engineering/Biotechnology Special Volume: Phytoremediation*. Springer Verlag, Heidelberg. (In Press).

Glass, D., 1999. U.S. and International Markets for Phytoremediation, 1999-2000. D. Glass Associates, Inc. Needham, MA.

Gordon, M., Choe, N., Duffy, J., Ekuan, G., Heilman, P., Muiznieks, I., Ruszaj, M., Shurtleff, B., Strand, S., Wilmoth, J., and L. Newman. 1998. Phytoremediation of Trichloroethylene with Hybrid Poplars. Environ Health Perspect. 106 (Suppl 4):1001-1004.

Gussman, C. 2001. August 2000 Field Activities, Edward Sears Site, New Gretna, New Jersey, Work Assignment 0-048 – Trip Report. Lockheed Martin Technology Services, Edison, New Jersey.

Gussman, C. 2002. Field Activities 2001, Edward Sears Property, New Gretna, New Jersey, Work Assignment 0-048- Status Report. Lockheed Martin Technology Services, Edison, New Jersey.

Griswold, Hays. September 28, 2000. U.S. Environmental Protection Agency Pollution Report.

Griswold, Hays. January 11, 2001. U.S. Environmental Protection Agency Pollution Report.

Griswold, Hays. August 15, 2001. U.S. Environmental Protection Agency Pollution Report.

Hauser, V., Gimon, D., and J. Horin. 1999. Draft Protocol for Controlling Contaminated Groundwater by Phytostabilization. Air Force Center for Environmental Excellence.

Hirsh, S., Burken, J., Compton, H., Schneider, W., and J. Wrobel. 2002. "Characterizing the Remedial Performance of a Phytoremediation Pilot Study: A Case Study from J-Field, Aberdeen Proving Ground, Maryland." Battelle Remediation of Chlorinated and Recalcitrant Compounds Conference Presentation, May 21, Monterey, California.

Interstate Technology and Regulatory Council. Phytoremediation Decision Tree Document. 1999.

Interstate Technology and Regulatory Council. Phytotechnology Technical and Regulatory Guidance Document. 2001.

Landmeyer, J. 2001. "Monitoring the Effect of Poplar Trees on Petroleum Hydrocarbon and Chlorinated-Solvent Contaminated Groundwater." International Journal of Phytoremediation. 3(1): 61-85.

Lee, R., Jones S., Kuniansky, E., Harvey, G., Lollar, B., and G. Slater. 2000. Phreatophyte Influence on Reductive Dechlorination in a Shallow Aquifer Contaminated with Trichloroethylene (TCE). International Journal of Phytoremediation, 2 (3): 193-211.

Ma, X. and J. Burken. 2002. "Fate of TCE after Uptake by Hybrid Poplar Trees." (In Press).

McCutcheon, S., and J. Schnoor. 2003 (Eds.). *Phytoremediation: Transformation and Control of Contaminants*. John Wiley and Sons, Inc. (In Press)

McLinn, E., Vondracek, J., and E. Aitchison. 2001. "Monitoring Remediation with Trembling Leaves: Assessing the Effectiveness of a Full-Scale Phytoremediation System." In: A. Leeson, E. Foote, M. Banks, and V. Magar (eds.) Phytoremediation, Wetlands, and Sediments, pp. 121-127. Battelle Press, Columbus, Ohio.

Mohn, M. 1997. Groundwater, Soil Gas, and Plant Gas Sampling Activities, Edward Sears Site, Work Assignment 2-120-Trip Report. Roy F. Weston, Edison, New Jersey.

Phytokinetics, Inc. Phytoremediation Pilot Study at the Solvent Recovery Services of New England (SRSNE) Superfund Site: 1998 Report for the Field-Scale Installation. North Logan, Utah.

Phytokinetics, Inc. Phytoremediation Pilot Study at the Solvent Recovery Services of New England (SRSNE) Superfund Site: 1999 Progress Report and 2000 Work Plan. North Logan, Utah.

Phytokinetics, Inc. Report of Field Work 2001 and Proposal for 2002. North Logan, Utah.

Phytokinetics, Inc. Sap Flow Measurements at the SRSNE Superfund Site, Southington, CT: Report of Field Work 2000 and Proposal for 2001. North Logan, Utah.

Pivetz, B. 2001. Ground Water Issue. Technology Innovation Office. EPA/540/S-01/500.

Remedial Technology Development Forum. 2002. *Evaluation of Phytoremediation for Management of Chlorinated Solvents in Soil and Groundwater*. Draft.

Rock, S., and G. Harvey. 2002. Innovative Technology Evaluation Report. Draft.

Schneider, W., Hirsh, S., Compton, H., Burgess, A., and J. Wrobel. 2002. "Analysis of Hydrologic Data to Evaluation Phytoremediation System Performance." Battelle Press, Columbus, Ohio. (In Press).

Schneider, W.,Wrobel, J., Hirsh, S., Compton, H., and D. Haroski. 2000. "The Influence of an Integrated Remedial System on Groundwater Hydrology." In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) *Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds*, pp. 477-481. Battelle Press, Columbus, Ohio.

Schnoor, J. "Phytoremediation of Soil and Groundwater." 2002. Ground-Water Remediation Technologies Analysis Center Technology Evaluation Report.

Susarla, S., Medina, V., and S. McCutcheon. 2002. Phytoremediation: An ecological solution to organic chemical contamination. Ecological Engineering. 18: 647-658.'

U.S. Environmental Protection Agency. 1997. "Pump and Treat of Contaminated Groundwater with Containment Wall at the Solvent Recovery Services of New England, Inc. Superfund Site Southington, Connecticut." Federal Remediation Technologies Roundtable Remediation Case Study, http://costperformance.org/html/00000136.html.

U.S. Environmental Protection Agency, Environmental Response Team. 1997. Final Report, Hydrogeological Investigation, Edward Sears Site, New Gretna, New Jersey.

U.S. Environmental Protection Agency, Region I. 1998. Amended Record of Decision, Tibbetts Road Superfund Site, Barrington, New Hampshire.

U. S. Environmental Protection Agency. 2000. Introduction to Phytoremediation. EPA 600-R-99-107.

U.S. Environmental Protection Agency. 2002. North Atlantic Treaty Organization (NATO)/ Committee on the Challenges of Modern Society (CCMS) Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III), 2001 Annual Report. EPA 542-R-02-001.

van der Lelie, D., Schwitzguebel, J., Glass, D., Vangronsveld, J., and A. Baker. 2001. "Assessing Phytoremediation's Progress." Environmental Science & Technology. 457A-452A.

Personal Communications

Government Organizations

U.S. Environmental Protection Agency
- Harold Compton, Aberdeen Proving Ground site
- Linda Fiedler, Technology Innovation Office
- Hays Griswold, Project Manager, Vernal Naples Truck Stop site
- Neil Handler, Project Manager, Tibbetts Road site
- Steven Hirsh, Aberdeen Proving Ground site
- Karen Lumino, Project Manager, SRSNE site
- Steven McCutcheon, Editor, *Phytoremediation: Transformation and Control of Contaminants* (In Press)
- George Prince, Project Manager, Edward Sears Property and Kauffman & Minteer sites
- Steven Rock, Carswell Naval Air Station site
- Terry Tanner, Project Manager, Calhoun Park site

U.S. Geological Survey
- Rick Dinicola, NUWC Keyport site
- Sandra Eberts, Carswell Naval Air Station site
- James Landmeyer, Beaufort and Calhoun Park sites

Air Force Center for Environmental Excellence
- Rafael Vazquez

U. S. Army
Gregory Harvey, Carswell Naval Air Station site

Academia

University of Missouri-Rolla
Joel Burken, Assistant Professor, Civil Engineering

University of Vermont
Andrea Porter, Graduate Assistant, Civil & Environmental Engineering

Private Companies

Applied Natural Sciences
Edward Gatliff

Applied Phytogenetics, Inc.
David Glass

Arcadis
Kathy Thalman

BP Amoco
David Tsao

CH2MHILL
Robert Tossell
James Jordahl

De Maximis
Bruce Thompson

Ecolotree, Inc.
Eric Aitchison

Lockheed Martin
Christopher Gussman

Phytokinetics
Nickolee Zollinger

Pro2Serve, Inc.
David Rieske

Roy F. Weston, Inc.
William Schneider

Roux Associates, Inc.
Walter Eifert

Sand Creek Consultants, Inc.
Christopher Rog

Thomas Consultants, Inc.
Paul Thomas

URS Corporation
Michael Meyer

Appendix 1: Field work involving the phytoremediation of VOC-contaminated groundwater

Ongoing Projects in the United States

Site (alphabetically by state)	Point of Contact*	Tree Species	Primary Contaminant	Year Implemented	Objectives	Performance to Date	Depth of Impact	Other Comments
CALIFORNIA								
Travis Air Force Base, California	Rafael Vazquez, Air Force Center for Environmental Excellence	480 red ironbark (*Eucalyptus sideroxylon* 'Rosea') trees on 3 acre demonstration site	TCE (490-17,000 ug/L), cis-1,2-DCE (5-120 ug/L)	November 1998	Hydraulic control of groundwater contaminant plume	Three to five more years of data is needed to establish tree impact on groundwater	16.4 ft below ground surface	N/A
ERP Site 17 Beale Air Force Base Marysville, California	Mr. Michael O'Brien Chief, Environmental Restoration Beale AFB (530) 634-3856 Michael.O'Brien@beale.af.mil Mr. Martin Barackman Project Manager CH2M HILL (530) 229-3401 mbarackm@CH2M.com	Cottonwood (*Populus fremontii)* *Live* Oak (*Quercus wislizenii*) Buttonwillow (*Cephalanthus occidentalis var. californicus*) Mulefat (*Baccharis salicifolia*) Narrow leaf willow (*Salix exigua*)	Trichloroethylene and related daughter products. Non-aqueous phase liquid (NAPL) is present at this site.	2000	Trees are planted over a 5 acre area surrounded by a subsurface slurry wall. Uptake of water by the trees is designed to lower groundwater levels inside the slurry wall containment area and prevent outward migration of contaminated groundwater.	Vegetation is established but not yet mature. Performance cannot yet be evaluated.	Groundwater levels inside the slurry wall need to be maintained at 12 to 14 ft below ground surface.	Although the primary purpose of the vegetation is to provide "phyto pumping", is anticipated that VOC mass removal will also occur as a result of transpiration through the plants.
Vandenberg Air Force Base, California	Rafael Vazquez, Air Force Center for Environmental Excellence	1,260 hybrid poplar (*P. trichocarpa x deltoides, P. trichocarpa x nigra, P. deltoides x maximoxiczii*) cuttings in one-acre area	TCE (69 J ug/L), cis-1,2-DCE (32 ug/L), PCE (380 ug/L), trans-1,2-DCE (2.6 ug/L)	August 2001	Hydraulic control of groundwater contaminant plume	Three to five more years of data is needed to establish tree impact on groundwater	Groundwater is 5-10 ft below ground surface	N/A
CONNECTICUT								
Solvent Recovery Services of New England - Southington, CT	Karen Lumino, USEPA Ari Ferro, Phytokinetics	950 hybrid poplar (DN-34), white willow (*Salix alba*), and native trees on 0.8 acres	TCE, cis-1,2 -DCE, 1,1,1-TCA, Toluene	May 1998	To augment and/or replace the existing overburden groundwater pump and treat system	Water use rates for 2001 averaged 7.8 gpd per tree for willows and 8.4 gpd per poplar. A fungal canker affected several poplar trees, which consequently may have to be replaced.	Groundwater is 4-12 ft below ground surface	See references provided in case study
FLORIDA								
NASA Kennedy Space Center Hydrocarbon Burn Facility, Cape Canaveral, Florida	Dr. Jacqueline Quinn, Kennedy Space Center	4,400 hybrid poplars (50% DN-34 and 50% OP-367) and understory grasses on 3 acres	Halogenated volatiles (TCE, cis-1,2-DCE, Vinyl Chloride), aromatic and polynuclear aromatic hydrocarbons (Naphthalene), metals. Total petroleum hydrocarbon concentration is 110-760 mg/L.	April 1998	Hydraulic control of plume, phytoextraction, phytovolatilization, rhizodegradation	Aft below ground surfaceer three growing seasons, the poplar trees did not access site groundwater because of stunted tree growth due to environmental stresses and there was no apparent impact on groundwater flow. The environmental stresses included drought conditions, absence of irrigation during first two growing seasons, competition from weeds and grasses for both water and nutrients, site soil conditions and depth to groundwater (7 to 10 ft below ground surface).	1-5 ft below ground surface	Northern hybrid poplar trees did not acclimate to sandy soils with little nutrients found in the coastal envrionment of Florida. A site with shallower groundwater or installation of an irrigation system at the root depth capable of providing water and nutrients may have resulted in greater tree growth. Aggressive understory grass should not be plannted at the same time as the trees if site soils are sandy and minor nutrient availability is reduced by soil pH. The site should be kept grass and weed freee until the trees are established. A southern variety of hybrid poplars or another tree species more acclimated to the climate would be more suitable for Florida sites.
ILLINOIS								
Fringe drain area - Argonne, Illinios	Ed Gattliff, Applied Natural Sciences, Inc.	809 hybrid poplars (*P. maximowiczii x trichocarpa* and *P. charkoweiiensis x incrassata*) and willow trees (*Salix alba* and prairie cascade) on 3.2 acres	TCE (less than 10 mg/L) and Tritium	1999	Hydraulic control of the aquifer and reduction of contaminant levels in the soil and groundwater	Early tree growth was severely limited as a result of early summer planting in 1999 and a cool summer in 2000. In 2001 and 2002, tree growth has substantially improved with poplar trees achieving 4-6 ft of growth per year. Hydraulic effects by the trees on groundwater were measurable in 2001. Measurable uptake of TCE and Tritium from groundwater is not expected to be realized until late in 2002 or 2003, because of the slow early growth of the trees.	20-30 ft below ground surface	a

Appendix 1: Field work involving the phytoremediation of VOC-contaminated groundwater

Site (alphabetically by state)	Point of Contact*	Tree Species	Primary Contaminant	Year Implemented	Objectives	Performance to Date	Depth of Impact	Other Comments
Unspecified manufacturing facility - Aurora, Illinois	Ed Gattliff, Applied Natural Sciences, Inc.	About 200 hybrid poplars (*P. maximowiczii x trichocarpa*) on concentrated plot with about 50 willows (*Salix pentandra*) on boundary	TCE (up to 25 mg/L)	2000	Hydraulic control and reduction of TCE contaminant levels in the aquifer	Trees have grown consistently (up to 8 ft/year for the poplar). Comparison of groundwater concentrations from pre-installation of the TreeMediation system and 2 growing seasons later indicate significant reduction of the TCE concentrations in the aquifer both at the source area and on the property boundary. Hydraulic effects on the groundwater flow have also been demonstrated.	10-15 ft below ground surface	N/A
Rochelle Terminal, Illinois	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using seed and poles of poplar varieties, deep-rooted prairie grasses and flowers	BTEX	2001-2002	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation and evapotranspiration	Monitoring of water levels and groundwater concentrations	10-15 ft below ground surface	N/A
Leachate interception buffer, northern Illinois	Eric Aitchison, Ecolotree, Inc.	Full-scale project of 900 hybrid poplars (DN-34), laurel leaf willows, and understory grasses on one acre site	Low concentrations of organics (primarily BTEX with Benzene at 4 ug/L, TCE at 2-5 ug/L, DCE at 1-70 ug/L)	2001-2002	To intercept shallow groundwater downgradient from active landfill, reduce mass of contaminant moving off-site, hydraulic containment	Survival rate is greater than 90%. Trees have grown 3-8 ft in 1.5 growing seasons. Have had substantial deer damage.	Groundwater is 2-4 ft below ground surface	N/A
INDIANA								
Whiting Refinery - J&L West, Indiana	David Tsao, Group Environmental Management Company, a BP affiliated company	Pilot-scale project using potted black alder, cottonwood, willow, Norway spruce, Austrian pine stock	Phenols, alkalinity	1998	Hydraulic control through evapotranspiration	Monitoring of water levels and sap flow	1-10 ft below ground surface	A Horizon soil on top of slag
Unspecified leaking underground storage tank site, Indiana	Louis Licht, Ecolotree, Inc.	Full-scale project of 350 hybrid poplars (DN-34) and understory grasses on 0.5 acres	BTEX (less than 2 mg/L)	November 2001	Hydraulic cap to hold residual contamination in place, to degrade residual contamination in soil, to cleanup contaminated groundwater, to reduce groundwater flow rates from the site	Greater than 95% survival	Groundwater is 3-6 ft below ground surface	N/A
IOWA								
Unspecified chlorinated solvent spill site, northern Iowa	Louis Licht, Ecolotree, Inc.	Full-scale project with 700 hybrid poplar trees (DN-34) on one acre site	PCE (up to 15 mg/L), TCE (up to 50 ug/L)	April 2002	To intercept PCE/TCE/DCE-contaminated groundwater water and promote their degradation, reduce mass flow of contaminants off-site	Greater than 95% survival	Groundwater is 9-11 ft below ground surface	Trees planted by trenching 10 ft below ground and planting 15 ft trees to bottom of trench
KANSAS								
Unspecified hydrocarbon spill site, southern Kansas	Eric Aitchison, Ecolotree, Inc.	Full-scale project using 204 hybrid poplar trees (DN-34) and understory grasses on a 0.3 acre site	Gasoline and diesel-range organics (up to 3,000 mg/kg in soil). Total volatile petroleum hydrocarbons range between 2 and 36 mg/L in groudwater)	January 2001	To intercept groundwater, create a hydraulic cap, and clean up contaminated soil	Some tree loss, likely due to soil or free product phytotoxicity. 75% survival after two growing seasons.	Groundwater is 9-11 ft below ground surface	Trees planted in 10 ft deep auger holes to access groundwater
Sugar Creek Refinery - T156, Kansas	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using whips of poplar varieties	BTEX, MTBE	2001	Rhizodegradation, phytodegradation, and evapotranspiration in the riparian zone	Monitoring of water levels, sap flow, and groundwater concentrations	0-2 ft below ground surface	N/A
KENTUCKY								
Louisville Terminal, Kentucky	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project with potted stock of poplar varieties	BTEX	2000	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation, and evapotranspiration	Monitoring of water levels and groundwater concentrations	10-15 ft below ground surface	N/A
LOUSIANA								
Unspecified oil transfer depot-Lafayette, Louisiana	Ed Gattliff, Applied Natural Sciences, Inc.	100 hybrid poplars (*P. maximowiczii x trichocarpa*) and willow on 0.5 acre plot	TCE (up to 353 ug/L)	1995	Remediation of TCE and its derivatives in a shallow aquifer	Poplar did not thrive in wet, heavy soil conditions	5 ft below ground surface	N/A
Combustion Superfund, Louisiana	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using eucalyptus, poplar, and native willow potted stock	Ethane Dichloride, Toluene Diamine	2000, with remainder of site scheduled for 2002	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation, and evapotranspiration	Monitoring of water levels and groundwater concentrations	5-10 ft below ground surface	N/A

Appendix 1: Field work involving the phytoremediation of VOC-contaminated groundwater

Site (alphabetically by state)	Point of Contact*	Tree Species	Primary Contaminant	Year Implemented	Objectives	Performance to Date	Depth of Impact	Other Comments
MARYLAND								
J-Field, Aberdeen Proving Ground - Edgewood, Maryland	Steve Hirsh, USEPA	Full-scale project consisting of about 850 hybrid poplars (P. deltoides x trichocarpa) and native trees planted on a five-acre plot	1,1,2,2 -Tetrachloroethane, TCE	1997	Hydraulic control	See case study description in body of text	Groundwater is about 3-12 ft below ground surface	See references provided in case study
MASSACHUSETTS								
Former Shell Bulk Oil Terminal West Boylston, Massachusetts	Brent Dyer Shell Global Solutions (US) Inc. 281-544-8565	Approximately 3900 *Populus deltoides x nigra* hybrid poplars planted on a six acre area	BTEX Petroleum hydrocarbons	2002	Hydraulic control, enhanced biodegradation	N/A	Groundwater <2 to 15 ft below ground surface.	N/A
MICHIGAN								
Unspecified manufacturing plant - Wayne, Michigan	Ed Gattliff, Applied Natural Sciences, Inc.	100 hybrid poplars (*P. maximowiczii x trichocarpa*) on 0.5 acre plot	TCE (up to 1.3 mg/L)	1997	Remediation of TCE and its derivatives in a shallow aquifer	After one year, TCE in groundwater was substantially reduced.	8 ft below ground surface	N/A
Unspecified chemical manufacturing plant, Michigan	Walt Eifert, Roux Associates, Inc.	4,500 hybrid poplars (OP-367 and DN-34) on 4.5 acres	Variety of contaminants (including VOCs)	1999	Hydraulic containment and in situ bioremediation	Better results with OP-367 poplars due to alkaline soils	8 ft below ground surface	N/A
NEBRASKA								
Unspecified municipal solid waste landfill, western Nebraska	Louis Licht, Ecolotree, Inc.	Full-scale project of 6,000 hybrid poplars (DN-34) and understory grasses on 6 acres	Leachate, TCE and DCE at about 1 mg/L	December 2000	Site consists of two areas: an upland area that was capped to prevent water from infiltrating into waste, and a downgradient area that is intended to intercept contaminated groundwater	Survival rate is greater than 95% at present time.	Groundwater is 6 ft below ground surface	N/A
NEW JERSEY								
Edward Sears Property, New Gretna, New Jersey	George Prince, USEPA	Pilot project with 118 *P. charkoweiiensis x incrassata* (NE-308) planted by deep-rooting on 0.33 acres	Dichloromethane, Trimethylbenzene, Xylene, TCE, Tetrachloroethylene	1996	Contaminant uptake, degradation in root zone	See case study description in body of text	Groundwater is about 9 ft below ground surface	See references provided in case study
Unspecified chemical manufacturing facility, New Jersey	Walt Eifert, Roux Associates, Inc. (WV)	800 hybrid poplars (DN-34) on 0.8 acre plot	BTEX	1998	Hydraulic containment of the perimeter of plume	N/A	6 ft below ground surface	N/A
Carteret Terminal, New Jersey	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using potted stock of poplar varieties	BTEX	1998	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation and evapotranspiration	Monitoring of water levels and groundwater concentrations	10-12 ft below ground surface	N/A
Kauffman & Minteer - Jobstown, New Jersey	George Prince, USEPA	265 hybrid poplar (*P. maximowiczii x trichocarpa*) and black willow (*Salix nigra*) on a five-acre site	TCE, cis-1,2-DCE	1998	Contaminant uptake, degradation in root zone	See case study description in body of text	Groundwater is 6-16 ft below ground surface	See references provided in case study
NEW HAMPSHIRE								
Tibbetts Road - Barrington, New Hampshire	Neil Handler, USEPA	1,400 one-year-old rooted *Populus deltoides x nigra*	Benzene (700 ug/L), cis-1.2-dichloroethene (100 ug/L), 4-Methyl-2-Pentanone (2,200 ug/L), Toluene (900 ug/L)	1998	Hydraulic control and contaminant removal	See case study description in body of text	Groundwater is 5-10 ft below ground surface	See references provided in case study
NORTH CAROLINA								
Aberdeen Pesticides Dump Site (APDS) - Aberdeen, North Carolina	Paul Thomas, Thomas Consultants, Inc.	Superfund project with approximately 2,000 *Populus charkoweiiensis x incrassata* (NE-308) and 2,000 *P. maximowiczii x trichocarpa* (NE-41) planted in trenches on about 9 acres	Xylene and pesticides	Pilot project started in 1997 and became full-scale in 1998.	Hydraulic control /contaminant removal	Groundwater uptake has been measured at 5,000 gpd/acre of one-year old trees (June 1999). Reduced levels of contaminants have been observed in downgradient wells. Ongoing monitoring of soil, sap flow, and groundwater levels through 2003.	3-17 ft below ground surface	500 *P. miximowiczii x trichocarpa* (NE-41) were deep-rooted in boreholes on 2 acres. Planting depth varied from 8-13 ft below ground surface.
NORTH DAKOTA								
Grand Forks Air Force Base, Grand Forks, North Dakota	Larry Olderbak, Grand Forks AFB Environmental	Eastern Cottonwood (*Populus deltoides* "Siouxland"), Carolina Poplar (*Populus canadensis* "Prairie Sky"), Imperial Carolina Poplar *P. deltoides x nigra* DN-34 (*Populus canadensis* "Imperial"), Russian Olive (*Elaeagnus angustifolia*) planted with 12 x 6 ft spacing	TCE (up to 4900 ug/L) and petroleum hydrocarbons (up to 2400 ug/L)	2002	Hydraulic control of the plume through groundwater uptake	Excellent growth so far	4-5 ft below ground surface	N/A
OHIO								
Unspecified plating facility - Findlay, Ohio	Ed Gattliff, Applied Natural Sciences, Inc.	30 hybrid poplars (*P. maximowiczii x trichocarpa*) on about 0.2 acre plot	TCE (up to 150 mg/L)	1997	Hydraulic control and reduction of TCE contaminant levels in the aquifer	Trees have grown at a rate of 4-8 ft/year. Results of the first 3 years indicated significant reduction of TCE concentrations in the aquifer in addition to demonstration of hydraulic effects on groundwater flow	10-15 ft below ground surface	N/A

Appendix 1: Field work involving the phytoremediation of VOC-contaminated groundwater

Site (alphabetically by state)	Point of Contact*	Tree Species	Primary Contaminant	Year Implemented	Objectives	Performance to Date	Depth of Impact	Other Comments
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio X-740 Area	David E. Rieske, Pro2Serve Technical Solutions (740) 897-2550 riesked@p2s.com	764 hybrid poplars (NE-19, DN-34, NM-6)	TCE (up to 2700 ug/L)	1999	Remediation of TCE and hydraulic control	Groundwater levels show direct impact, analytical results less profound. Up to 30 ft growth in 2 years.	Contaminated semi-confined aquifer is 32 ft below ground surface. Impact is aided by natural upward flow through sand-filled borings into bottom of 10 ft deep trenches.	N/A
OKLAHOMA								
Altus Air Force Base, Oklahoma	Rafael Vazquez, Air Force Center for Environmental Excellence	109 10-gallon *Populus x Canadensis Nor'easter* trees on a 0.3 acre demonstration site	TCE (2-1,400 ug/L), cis-1,2-DCE (1-540 ug/L), PCE (2-1,200 ug/L)	March 1999	Hydraulic control of groundwater contaminant plume	Three to five more years of data is needed to establish tree impact on groundwater.	Groundwater is 5-8 ft below ground surface	N/A
SOUTH CAROLINA								
Gasoline Station near Beaufort, South Carolina	Jim Landmeyer, USGS	Study site with about 20 native mature oak (*Quercus virginiana*) trees on about 1 acre site	MTBE (up to 100 mg/L), BTEX (up to 20 mg/L)	Trees are up to 40 years old, but monitoring began in 1997	To see if trees were responsible for remediating groundwater contaminant plume	MTBE and BTEX detected in tree cores	Groundwater is about 13 ft below ground surface	b
Calhoun Park Area, Charleston, South Carolina	Terry Tanner, USEPA	600 hybrid poplars (*P. charkoweiiensis x incrassata and P. deltoides x nigra*) planted over 0.4 acres	PAHs (naphthalene up to 20 mg/L), BTEX (up to 5 mg/L) - Plume and DNAPL covers about a 30,000 square foot area	Dec. 1998	Contaminant uptake, degradation in root zone	Monitoring of groundwater elevation and contaminant concentration	Groundwater is 3-12 ft below ground surface	N/A
Savannah River, South Carolina	Dr. Lee Newman, University of South Carolina and Cassandra Bayer, Bechtel Savannah River, Inc.	8 1/4-acre plots of hybrid poplars and loblolly pines	TCE (about 1.5 mg/L), PCE	October 2001	VOC Separation, Water management and polishing of remaining VOCs in dilute plume fringe through phyto-irrigation	April 2002 tissue sampling results do not indicate the presence of TCE	Water table is approximately 150 ft below ground surface, however compliance point is at 8 ft.	N/A
SOUTH DAKOTA								
Ellsworth Air Force Base, South Dakota	Rafael Vazquez, Air Force Center for Environmental Excellence	1,027 hybrid poplars (NM-6, DN-17, and DN-182) planted on one-acre deomnstration site	TCE (240 ug/L), cis-1,2-DCE (100 ug/L)	June 2001	Hydraulic control of groundwater contaminant plume	Three to five more years of data is needed to establish tree impact on groundwater.	Groundwater is 5-30 ft below ground surface	N/A
TENNESSEE								
Unspecified creosote-contaminated site - Oneida, Tennessee	Louis Licht, Ecolotree, Inc.	800 hybrid poplars (DN-34) and understory grasses on one acre site	PAHs (napthalene up to 3 mg/L)	1997	Hydraulic control, rhizodegradation, soil stabilization	Dissolved oxygen, aqueous Fe (II), and PAH concentrations indicated in situ aerobic and Fe(III)-reducing zones of PAH degradation.	10 ft below ground surface	c,d,e
TEXAS								
Carswell Naval Air Station - Fort Worth, Texas	Greg Harvey, Wright-Patterson Air Force Base	660 *Populus deltoides* (whips and calipers) planted on 0.5 acre area	TCE (230 - 970 ug/L), cis-1,2-DCE (24-131 ug/L)	1996	Phytoremediation enhanced in situ bioremediation, hydraulic control	See case study description in body of text	Groundwater is 6-11 ft below ground surface	See references provided in case study
Unspecified site - Houston, Texas	Jerald Schnoor, University of Iowa	1,370 hybrid poplar trees (DN-34, NE-19)	MTBE	1998	Hydraulic control and contaminant removal	Water uptake by trees estimated at 4 gpd	Groundwater is 9-10 ft below ground surface	f
Texas City Chemicals - Plant A, Texas	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using potted eucalyptus stock	PAHs	2000	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation and evapotranspiration	Monitoring of water levels, gourndwater concentrations, and tissue concentrations	10-15 ft below ground surface	N/A
UTAH								
Former Chevron Light Petroleum Products Terminal - Ogden, Utah	Ari Ferro, Phytokinetics	40 hybrid poplars (Imperial Carolina, P. deltoides x nigra, DN-34)	BTEX, petroleum hydrocarbons (5 - 10,000 ug/L)	1996	To control migration of contaminant plume	Although water use estimated an average of 445 gpd in 1999, water table elevation data did not indicate a depression in the water table	Groundwater is 4-9 ft below ground surface	See references provided in case study
Vernal Naples Truck Stop - Vernal, Utah	Hays Griswold, USEPA	300 Sioux-land poplar trees	Gasoline and MTBE	1998		See case study description in body of text		See references provided in case study
Hill Air Force Base, Utah	Rafael Vazquez, Air Force Center for Environmental Excellence	Sites A and B consist of 43 and 100 planted cuttings of hybrid poplar (P. trichocarpa x deltoides, P. trichocarpa x nigra)	TCE, cis-1,2-DCE, trans-1,2-DCE	July 2001	Hydraulic control of groundwater contaminant plume	Three to five more years of data is needed to establish tree impact on groundwater	At Site A, groundwater is between 15 and 20 ft below the surface. At Site B, groundwater is between 5 and 10 ft below the surface.	N/A
WASHINGTON								
Naval Underwater Weapons Center, Keyport, Washington	Michael Meyer, URS Corporation	Full-scale implementation at Superfund site with 900 hybrid poplar (15-029) cuttings	TCE, Vinyl Chloride, cis-1,2-DCE	April 1999	Reduce VOC concentrations	Shallow groundwater elevation data shows no significant effect from the phytoremediation plantation. No significant effect on VOC concentrations is expected until the trees mature.	Groundwater is about 5 ft below ground surface	g
Fairchild Air Force Base, Washington	Rafael Vazquez, Air Force Center for Environmental Excellence	1,134 hybrid poplar (P. trichocarpa x deltoides, P. trichocarpa x nigra, P. deltoides x maximoxiczii) cuttings on 1 acre demonstration site	TCE (381 ug/L), cis-1,2-DCE (1.44 ug/L), PCE (1.07 ug/L)	April 2001	Hydraulic control of groundwater contaminant plume	Three to five more years of data is needed to establish tree impact on groundwater	Groundwater is 9-11 ft below ground surface	N/A
WEST VIRGINIA								

Appendix 1: Field work involving the phytoremediation of VOC-contaminated groundwater

Site (alphabetically by state)	Point of Contact*	Tree Species	Primary Contaminant	Year Implemented	Objectives	Performance to Date	Depth of Impact	Other Comments
Leaking Underground Gasoline Storage Tank - Widen, West Virginia	Paul Thomas, Thomas Consultants, Inc.	Full-scale project with approximately 100 *Populus charkoweiiensis x incrassata* (NE-308) planted on about 0.5 acres	BTEX in soil and shallow groundwater	1994	Reduce residual hydrocarbons in capillary fringe, and remediate BTEX in shallow groundwater	Non-dectable concentrations for the last five years	Groundwater is 4 ft below surface	N/A
WISCONSIN								
Ashland, Inc. - Milwaukee, Wisconsin	Eric Aitchison, Ecolotree, Inc.	Full-scale project with 272 2-year hybrid poplar trees in the groundwater treatment zone	PCE, TCE, cis-1,2-DCE, TCA, 1,2-DCA, Vinyl Chloride, Methylene Chloride, 2-Butanone, BTEX	May 2000	To reduce the discharge of affected groundwater to a downgradient river	The phytoremediation system appears to be intercepting shallow groundwater, and also appears to accelerate biodegradation in shallow groundwater.	Groundwater is about 10 ft below surface	h
Petroleum Bulk Plant, Wisconsin	Christopher Rog, Sand Creek Consultants	Hybrid poplar NM-6, pumping capabilities and know to be high for this clone in our region.	Diesel Range Organics (1-11 ug/L); Gasoline Range Organics (50 ug/L), Benzene (< 1,000 ug/L)	2002	Plume control and use of root exudates to break down contaminants.	N/A	Groundwater is 5 ft below ground surface	Fencing and using weedblock to exclude weeds and encourage tree growth. Spacing 3 ft by 3 ft.
WYOMING								
Casper Refinery - Hydraulic Gradient, Wyoming	David Tsao, Group Environmental Management Company, a BP affiliated company	Pilot-scale project using poles of poplar varieties	BTEX	2001	Hydraulic control through evapotranspiration	Monitoring of water levels and groundwater concentrations	10-15 ft below ground surface	Supplement Groundwater Extraction System
UNSPECIFIED STATE								
Unspecified petrochemical plant, Northeastern Region	Walt Eifert, Roux Associates, Inc. (WV)	3,000 hybrid poplars (DN-34) on 2.7 acres	Benzene (200 ug/L), Toluene (15 ug/L), Ethylbenzene (40 ug/L), Xylene (80 ug/L)	2000	Hydraulic control and BTEX remediation	Available in 2004	15 ft below ground surface	N/A

***Source of information unless otherwise specified.**

Appendix 2: Planned Projects

Site (alphabetically by state)	Point of Contact*	Tree Species	Primary Contaminant	Implementation Date	Objectives	Monitoring	Depth of Impact
Sugar Creek Refinery - Norledge, Kansas	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using plugs, seed, potted stock of deep-rooted prairie grasses and flowers, Poplars, and ornamental trees	BTEX, MTBE	Scheduled for 2002	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation and evapotranspiration	Monitoring of water levels, sap flow, and groundwater concentrations	5-15 ft
Unspecified chemical manufacturing facility, Michigan	Walt Eifert, Roux Associates, Inc. (WV)	Hybrid poplar	Toluene and Xylene (4-100 mg/L)	Currently feasibility study, will be implemented in spring 2003	Hydraulic control and rhizodegradation	N/A	0-15 ft
Raleigh SS825, North Carolina	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using plus and poles of Poplar varieties, deep-rooted prairie grasses and flowers	BTEX, MTBE	Scheduled for 2002	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation and evapotranspiration	Monitoring of water levels and groundwater concentrations	5-15 ft
Canton Terminal, Ohio	David Tsao, Group Environmental Management Company, a BP affiliated company	Full-scale project using poles of Poplar varieties	BTEX	Scheduled for 2002	Hydraulic control and groundwater remediation through rhizodegradation, phytodegradation and evapotranspiration	Monitoring of water levels and groundwater concentrations	10-20 ft
Unspecified, South Carolina	David McMillan, Natresco	Hybrid poplar and willow	PCE, TCE, CCl_4	Several years	Contaminant removal, retardation of plume movement, and control of local groundwater recharge	N/A	N/A

***Source of information unless otherwise specified.**

Appendix Notes

[a] Quinn, J., Negri, M., Hinchman, R., Moos, L., Wozniak, J., and E. Gatliff. 2001. “Predicting the Effect of Deep-Rooted Hybrid Poplars on the Groundwater Flow System at a Large-Scale Phytoremediation Site”. International Journal of

[b] Landmeyer, J., Vroblesky, D., and P. Bradley. 2000. MTBE and BTEX in Trees above Gasoline-Contaminated Ground Water. In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) Case Studies in the Remediation of

[c] Novak, J., and M. Widdowson. “Characterization of Degradation Mechanisms for PAH Compounds.” Battelle Remediation of Chlorinated and Recalcitrant Compounds Conference Presentation. 5/20/02. Monterey, California.

[d] Robinson, S., Novak, J., Widdowson, M., and M. Elliot. 2001. “Microbial Degradation of PAHs under Various Redox Conditions at a Creosote-Contaminated Site”. In:A. Leeson, E. Foote, M. Banks, and V. Magar (eds.) Phytoremediation,

[e] Novak, J., Widdowson, M., Elliot, M., and S. Robinson. 2000. “Phytoremediation of a Creosote Contaminated Site – A Field Study”. In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) Bioremediation and

[f] Hong, M., Farmayan, W., Dortch, I., Chiang, C., McMillan, S., and J. Schnoor. 2001. "Phytoremediation of MTBE from a Groundwater Plume". Environ. Sci. Technol. 35: 1231-1239.

[g] Rohrer, W., Newman, L., and B. Wallis. 2000. “Monitoring Site Constraints at NUWC Keyport's Hybrid Poplar Phytoremediation Plantation”. In: G. Wickramanayake, A. Gavaskar, B. Alleman, and V. Magar (eds.) Bioremediation and

[h] McLinn, E., Vondracek, J., and E. Aitchison. 2001. “Monitoring Remediation with Trembling Leaves: Assessing the Effectiveness of a Full-Scale Phytoremediation System”. In: A. Leeson, E. Foote, M. Banks, and V. Magar (eds.)