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Phytoremediation of Groundwater at Air Force Plant 4 Carswell, Texas

Innovative Technology Evaluation Report

SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

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Phytoremediation of Groundwater at Air Force Plant 4

Carswell, Texas

Innovative Technology Evaluation Report

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
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Notice

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication had been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Hugh McKinnon, Director
National Risk Management Research Laboratory

Abstract

A demonstration of a Phytoremediation Groundwater Treatment system was conducted at the Carswell Naval Air Sation (NAS) Golf Club in Fort Worth, Texas to investigate the ability of purposely planted eastern cottonwood trees, *Populus deltoides*, to help remediate shallow TCE-contaminated groundwater in a subhumid climate. Specifically, the study was undertaken to determine the potential for a planted system to hydraulically control the migration of contaminated groundwater, as well as biologically enhance the subsurface environment to optimize in-situ reductive dechlorination of chlorinated ethenes present (trichloroethene and cis-1,2-dichloroethene) in the shallow aquifer system beneath a portion of the golf course. *Populus deltoides*, like other phreatophytes, have long been recognized as having the ability to tap into the saturated zone to extract water for metabolic processes. Based upon this characteristic the species was considered well suited for applications where shallow aquifers are contaminated with biodegradable organic contaminants. A planted system of cottonwood trees is believed to effectuate two processes that aid and accelerate contaminant attenuation. First, transpiration of groundwater through the trees is believed to be able to modify and hopefully control the hydraulic groundwater gradient. This can minimize the rate and magnitude of migrating contaminants downgradient of the tree plantation. Secondly, the establishment of the root biomass, or rhizosphere, promotes microbial activity and may enhance biodegradative processes in the subsurface. To assess the performance of the system, hydrologic and geochemical data were collected over a three-year period (August 1996 through September 1998). In addition to investigating changes in groundwater hydrology and chemistry, the trees were studied to determine important physiological processes such as rates of water usage, translocation and volatilization of these volatile organic compounds, and biological transformations of chlorinated ethenes within the plant organs.

The demonstration site is situated about one mile from the southern area of the main assembly building at Air Force Plant 4 (Plant 4) at the Carswell NAS. The assembly building is the primary suspected source of TCE at the demonstration site. The evaluation of this technology application was a joint effort between the U.S. Air Force (USAF), the U.S. Geological Survey, the U.S. Forest Service, the Department of Defense's (DoD's) Environmental Security Technology Certification Program (ESTCP), and the U.S. EPA's SITE program.

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Acronyms, Abbreviations and Symbols

A	Cross-Sectional Area of Aquifer
AACE	American Association of Cost Engineers
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AQCR	Air Quality Control Regions
AQMD	Air Quality Management District
ARARs	Applicable or Relevant and Appropriate Requirements
ASC/ENV	Aeronautical Systems Center Acquisition, Environmental, Safety and Health Division
ATTIC	Alternative Treatment Technology Information Center
BGS	Below Ground Surface
BFDP	Biofuel Feedstock Development Program
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CERI	Center for Environmental Research Information
CFR	Code of Federal Regulations
CGC	Carswell Golf Club
cm/s	centimeters/second
cm	Centimeter
CWA	Clean Water Act
d	day
DCE	Dichloroethene
DO	Dissolved Oxygen
DoD	Department of Defense
DoE	Department of Energy
ESTCP	Environmental Security Technology Certification Program
ft	feet
g	gram
gptpd	Gallons per Tree per Day
ha	Hectare
hr	Hour
I	Hydraulic Gradient
IRP	Installation Restoration Program
ITER	Innovative Technology Evaluation Report
K	Hydraulic Conductivity
Kg	Kilogram
m	Meter
m/d	meters/day
MCLGs	Maximum Contaminant Level Goals
MCLs	Maximum Contaminant Levels
mg/L	milligrams per liter

Acronyms, Abbreviations and Symbols(Cont'd)

mm	Millimeter
MPN	Most Probable Number
NAAQS	National Ambient Air Quality Standards
NAS	Naval Air Station
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NRMRL	National Risk Management Research Laboratory
O&M	Operation & Maintenance
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PA	Preliminary Assessment
PCBs	Polychlorinated Biphenyls
POTW	Publicly Owned Treatment Works
PPE	Personal Protective Equipment
Q	Volumetric Flux
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
SAIC	Science Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SWDA	Solid Waste Disposal Act
TCE	Trichloroethene
TEAP	Terminal Electron-Accepting Process
TER	Technology Evaluation Report
TOC	Total Organic Carbon
TSCA	Toxic Substances Control Act
TSD	Treatment Storage and Disposal
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	Vinyl Chloride
VISITT	Vendor Information System for Innovative Treatment Technologies
VOCs	Volatile Organic Compounds

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SECTION 1
INTRODUCTION

This section provides a discussion on the fate of fuel and solvent contaminants in groundwater systems, the limits of intrinsic remedial mechanisms, biodegradation of fuel products and chlorinated compounds, the three chlorinated solvent plume behavior types and their implications on reductive dechlorination, background information on the study site and the field test, background information about the Superfund Innovative Technology Evaluation (SITE) Program, the Environmental Technology Certification Program (ESTCP), the purpose of this Innovative Technology Evaluation Report (ITER), and the Phytoremediation of groundwater process. For additional information about the SITE Program, this technology, and the demonstration site, key contacts are listed at the end of this section.

1.1 Background

Fuels and chlorinated solvents are commonly found in groundwater. In the last twenty years the persistence and behavior of fuels and chlorinated solvents in ground water have been the subject of intense investigation and vociferous debate. Both fuels and chlorinated solvents can naturally attenuate if the appropriate conditions exist in the subsurface. Natural attenuation in groundwater systems results from the integration of several subsurface mechanisms that are classified as either destructive or non destructive (Wiedemeier, 1996). Biodegradation is the most important destructive mechanism. Nondestructive mechanisms include sorption, dispersion, dilution from recharge, and volatilization (Wiedemeier, 1996). The behavior of fuels and chlorinated solvents in the subsurface are different from one another depending on the availability of electron acceptors and electron doners in the subsurface: The most significant difference between fuel products and chlorinated solvents is that usually fuel plumes don't move and chlorinated solvent plumes do.

The biodegradation of fuel products is limited by electron acceptor availability (Wiedemeier, 1996). Fortunately there is an adequate supply of electron acceptors in most hydrologic settings. Accordingly, most fuels plumes degrade faster than they move (Chappelle, 2000). The long term behavior of chlorinated solvents is more difficult to predict than fuel plumes. The biodegradation of chlorinated solvents begins in the saturated subsurface where native or anthropogenic carbon is used as an election donor, and dissolved oxygen is utilized first for the prime electron acceptor (Wiedemeier, 1996). Once dissolved oxygen is depleted, anaerobic microorganisms most often use available electron acceptors in the following order: nitrate, Fe(III) hydroxide, sulfate, and carbon dioxide (Chappelle, 2000). In the absence of nitrate and dissolved oxygen, chlorinated solvents compete with other electron acceptors and donors especially sulfate and carbon dioxide. The most important anaerobic process for the natural biodegradation of chlorinated solvents is reductive dechlorination. When a chlorinated solvent is used as an electron acceptor, a chlorine atom is removed and replaced with a hydrogen atom. Electron donors include fuel hydrocarbons, landfill leachate or natural organic carbon. If the subsurface is depleted of electron donors before chlorinated solvents are removed, microbial reductive dechlorination will cease (Wiedemeier, 1996). Plumes of chlorinated solvents can naturally attenuate but almost 80% of the time they do not due to the lack of electron donors (Chappelle, 2000).

Chlorinated solvent plumes exhibit three types of behavior depending on the amount of solvent, the amount of biologically available organic carbon in the aquifer, the distribution and concentration of natural electron acceptors and types of electron acceptors (Wiedemeier, 1996). Type 1 behavior occurs when the primary substrate is anthropogenic carbon (e.g. benzene, toluene, xylene, or landfill leachate). The microbial degradation of this anthropogenic carbon drives reductive dechlorination. Type 2 behavior prevails in areas that have high concentrations of biologically available native organic carbon. Type 3 behavior dominates in areas that are lacking an adequate amount of native and or anthropogenic carbon and concentrations of dissolved oxygen that are greater than 1.0 mg/L. Reductive dechlorination does not occur under Type 3 conditions. Type 3 conditions commonly prevail at Department of Defense (DoD) sites resulting in very large unattenuated plumes.

The TCE groundwater plume beneath a portion of the Carswell Golf Club near Fort Worth, Texas is a prime example of a site characterized by Type 3 behavior. This site was chosen to field test an innovative phytoremediation process also referred to as the Short Rotation Woody Crop Groundwater Treatment (SRWCGT) system. The SRWCGT system was tested to determine the contribution of higher plants in (1) accelerating and enhancing the bioremediation and phytodegradation of chlorinated ethenes from a shallow aquifer; and (2) mitigating the migration of the contaminant plume through gradient control. The evaluation of this technology application was a joint effort between the U.S. Air Force (USAF), the U.S. Geological Survey, the U.S. Forest Service, the DoD's Environmental Security Technology Certification Program (ESTCP), and the U.S. EPA's SITE program.

The system is an application of phytoremediation technology designed and implemented by the USAF under the DoD ESTCP. The ESTCP is a corporate DoD program that promotes innovative, cost-effective environmental technologies through demonstration and validation at DoD sites. ESTCP's goal is to demonstrate and validate promising innovative technologies that target the DoD's most urgent environmental needs through their implementation and commercialization. These technologies provide a return on investment through cost savings and improved efficiency. ESTCP's strategy is to select lab-proven technologies with broad DoD and market application. These technologies are aggressively moved to the field for rigorous trials that document their costs, performance, and market potential.

The demonstration investigated the use of a phreatophytic tree, *Populus deltoides*, as a rapidly growing plant species that may accelerate natural processes that promote contaminant degradation as well as control hydraulic gradient. *Populus deltoides*, like any tree or any other living organism for that matter, is a complex structure derived ultimately from enzyme-catalyzed reactions regulated by its genes (Dickman, 1983). The study of the derivative of these biochemical reactions i.e. the functioning of the tree or any of its parts as an organized entity is tree physiology. (Dickmann, 1983) There are several different approaches to planting trees currently available. These range from deep auguring individual poles to the capillary fringe employing proprietary planting techniques to employing short rotation woody crop techniques. These planting approaches have their indications, contradictions and their various champions within the phytoremediation arena. Short rotation woody/energy crop technology was developed by the Department of Energy's Biofuel Feedstock Development Program (BFDP) at Oak Ridge National Laboratory (ORNL). The mission of the BFDP is to develop and demonstrate environmentally acceptable crops and cropping systems for producing large quantities of low cost high quality biomass feedstocks The research strategy of the BFDP is designed to maximize the economic returns, reduce environmental impacts and establish sustainable biomass systems that optimize per unit area productivity for members of the Populus and Salix genera over a substantially large portion of the U.S. To date, the BFDP has screened more than 125 tree and non-woody species and selected a number of model species for development as energy crops. Former President William Clinton issued an executive order calling for increased use of trees and crops as environmentally friendly sources of energy.

This demonstration investigated the use of a phreatophytic tree planted for use in phytoremediation of TCE-contaminated groundwater. *Populus deltoides*, commonly known as the cottonwood, is a rapidly growing tree that may accelerate natural processes that promote contaminant degradation as well as control hydraulic gradient. *Populus deltoides*, like other phreatophytes, has the ability to tap into the saturated zone to extract water for metabolic processes. Therefore, this species is well suited for applications where shallow aquifers are contaminated with biodegradable organic contaminants. The planted system is believed to effectuate two processes that aid and accelerate contaminant attenuation. First, transpiration of groundwater through the trees is believed to be able to modify and hopefully control the hydraulic groundwater gradient. This can minimize the rate and magnitude of migrating contaminants downgradient of the tree plantation. Secondly, the establishment of the root biomass, or rhizosphere, promotes microbial activity and may enhance biodegradative processes in the subsurface. A technology demonstration was designed to determine the effectiveness of the system to control hydraulic gradient and enhance biodegradative processes. As previously mentioned, the demonstration took place at the Carswell Golf Club (CGC) at the Naval Air Station (NAS) Fort Worth, which is adjacent to Air Force Plant 4. Specifically, the site is on the north side of the CGC west of the 8th green about 1 mile from the southern area of the main assembly building at Plant 4. The assembly building is the suspected source of TCE at the demonstration site. In April of 1996 approximately 660 trees were planted in two plots at the site.

Plant 4 was constructed in 1942 and currently produces F-16 aircraft, radar units, and various aircraft and missile components. General Dynamics operated the manufacturing facility from 1953 to 1994 when Lockheed took over operations. Since 1953, Plant 4 has produced B-36, B-58, and F-111 aircraft.

Historically, the manufacturing processes at Plant 4 have generated an estimated 5,500 to 6,000 tons of waste per year, including waste solvents, oils, fuels, paint residues, and miscellaneous spent chemicals. Throughout most of Plant 4's history, the waste oil, solvents, and fuels were disposed of at onsite landfills or were burned in fire training exercises.

Plant 4 is on the National Priorities List and is being remediated in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA).

Potential contamination at Plant 4 was first noted by a private citizen in September 1982. TCE may have leaked from the degreasing tanks in the assembly building at Plant 4 and entered the underlying aquifer over the course of decades. An Installation Restoration Program (IRP) was initiated in 1984 with a Phase I Records Search by CH2M Hill (CH2M Hill 1984). The U.S. Army Corps of Engineers (USACE) was retained in June of 1985 to further delineate groundwater conditions in the East Parking Lot area of Plant 4. The USACE constructed six monitoring wells (U.S. Army Corps of Engineers 1986). Ongoing groundwater sampling in the East Parking Lot area of Plant 4 has continued for the purpose of monitoring this plume.

The TCE plume appears to be migrating in an easterly to southeasterly direction. It appears to have migrated under the East Parking Lot and towards the NAS Fort Worth. The plume fingers toward the east with the major branch of the plume following a paleochannel under the flight lines to the south of the phytoremediation demonstration site, where it has undergone remediation with a pump and treat system. Another branch of the plume appears to follow a paleochannel to the north of the demonstration site.

Historic activities other than the operations at the assembly building, however, may have contributed to the TCE plume at the phytoremediation site. Several former landfills have been identified near the CGC where drums of TCE have been found . The former landfills appear to be upgradient and crossgradient from the demonstration site; however, insufficient groundwater level data and aquifer testing reports are available to determine whether these former landfills are actually sources.

1.2 Brief Description of the SITE Program and Reports

The SITE Program is a formal program established by EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, demonstration, and use of new or innovative technologies to clean up Superfund sites across the country.

The SITE Program's primary purpose is to maximize the use of alternatives in cleaning hazardous waste sites by encouraging the development and demonstration of new, innovative treatment and monitoring technologies. It consists of three major elements discussed below:

- the Demonstration Program,
- the Monitoring and Measuring Technologies Program, and
- the Technology Transfer Program.

The objective of the Demonstration Program is to develop reliable performance and cost data on innovative technologies so that potential users can assess the technology's site-specific applicability. Technologies evaluated are either available commercially or close to being available for full-scale remediation of Superfund sites. SITE demonstrations usually are conducted on hazardous waste sites under conditions that closely simulate full-scale remediation conditions, thus assuring the usefulness and reliability of information collected. Data collected are used to assess: (1) the performance of the technology, (2) the potential need for pre- and post-treatment processing of wastes, (3) potential operating problems, and (4) the approximate costs. The demonstrations also provide opportunities to evaluate the long-term risks, capital and O&M costs associated with full-scale application of the subject technology, and limitations of the technology.

Existing technologies and new technologies and test procedures that improve field monitoring and site characterizations are identified in the Monitoring and Measurement Technologies Program. New technologies that provide faster, more cost-effective contamination and site assessment data are supported by this program. The Monitoring and Measurement Technologies Program also formulates the protocols and standard operating procedures for demonstrating methods and equipment.

The Technology Transfer Program disseminates technical information on innovative technologies in the Demonstration, and the Monitoring and Measurement Technologies Programs through various activities. These activities increase the awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of technology transfer activities is to develop interactive communication among individuals requiring up-to-date technical information.

1.3 The SITE Demonstration Program

Technologies are selected for the SITE Demonstration Program through annual requests for proposals. ORD staff review the proposals to determine which technologies show the most promise for use at Superfund sites. Technologies chosen must be at the pilot- or full-scale stage, must be innovative, and must have some advantage over existing technologies. Mobile and in-situ technologies are of particular interest.

Once EPA has accepted a proposal, cooperative agreements between EPA and the developer establish responsibilities for conducting the demonstrations and evaluating the technology. The developer is responsible for demonstrating the technology at the selected site and is expected to pay any costs for transport, operations, and removal of the equipment. EPA is responsible for project planning, sampling and analysis, quality assurance and quality control, preparing reports, disseminating information, and transporting and disposing of treated waste materials.

The results of this evaluation of the SRWCGT process are published in this Innovative Technology Evaluation Report. The ITER is intended for use by remedial managers making a detailed evaluation of the technology for a specific site and waste.

1.4 Purpose of the Innovative Technology Evaluation Report (ITER)

This ITER provides information on the SRWCGT process and includes a comprehensive description of the demonstration and its results. The ITER is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision makers in implementing specific remedial actions. The ITER is designed to aid decision makers in further evaluating specific technologies when considering applicable options for particular cleanup operations. This report represents a critical step in the development and commercialization of a treatment technology.

To encourage the general use of demonstrated technologies, EPA provides information regarding the applicability of each technology to specific sites and wastes. The ITER includes information on cost and performance, particularly as evaluated during the demonstration. It also discusses advantages, disadvantages, and limitations of the technology.

Each SITE demonstration evaluates the performance of a technology in treating a specific waste. The waste characteristics of other sites may differ from the characteristics of the treated waste. Therefore, a successful field demonstration of a technology at one site does not necessarily ensure that it will be applicable at other sites. Data from the field demonstration may require extrapolation for estimating the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

1.5 Technology Description

The SRWCGT process is a phytoremediation technology that relies on the use of higher plants to augment *in situ* biodegradative reactions as well as control hydraulic gradient to minimize the transport of contaminants. The system evaluated at the Carswell Golf Club was designed to intercept and treat a TCE plume using strategically placed plantations of the Eastern Cottonwood trees (*Populus deltoides*). However, the technology is generally applicable to most biodegradable organic compounds. Figure 1-1 depicts the remediation mechanisms of the process.

Phytoremediation has received heightened attention as a mechanism to augment and accelerate natural degradative processes. Phytoremediation is the use of higher plants for remediating anthropogenically contaminated environments. Phytoremediation relies on several plant physiological processes to treat contaminants *in situ*. These generally fall into the following categories:

1. Degradation or the facilitation of degradation of organic contaminants alone or via microbial associations within the plant rhizosphere;
2. Hyperaccumulation or sequestering of inorganic contaminants within plant parts;
3. Binding of contaminants within plant organs;
4. Volatilization of organic contaminants from the rhizosphere and transpiration into the atmosphere.

Plants have evolved biological detoxification mechanisms over several hundred million years. Previous work has indicated that plants such as poplars and corn can metabolize TCE to trichloroethanol, trichloroacetic acid, dichloroacetic acid, and carbon dioxide (Schnoor and Kurimski 1995). Schnoor (1995b) suggests that a significant portion of TCE taken up by such plants is transformed and/or bound irreversibly to the biomass. Mass transfer limitations of organic compounds in soil due to low solubility and high soil adsorption, however, can limit plant uptake of many compounds. Highly lipophilic compounds such as polychlorinated biphenyls (PCBs) are generally so strongly bound to soil that they do not become bioavailable to either plants or microbes. Moderately lipophilic substances, such as TCE, can move through the soil to the position of the rhizosphere and are the most likely candidates for phytoremediation.

In general, phytoremediation has the potential to mitigate groundwater contamination in two ways: (1) withdrawal of groundwater from an aquifer to minimize migration of a

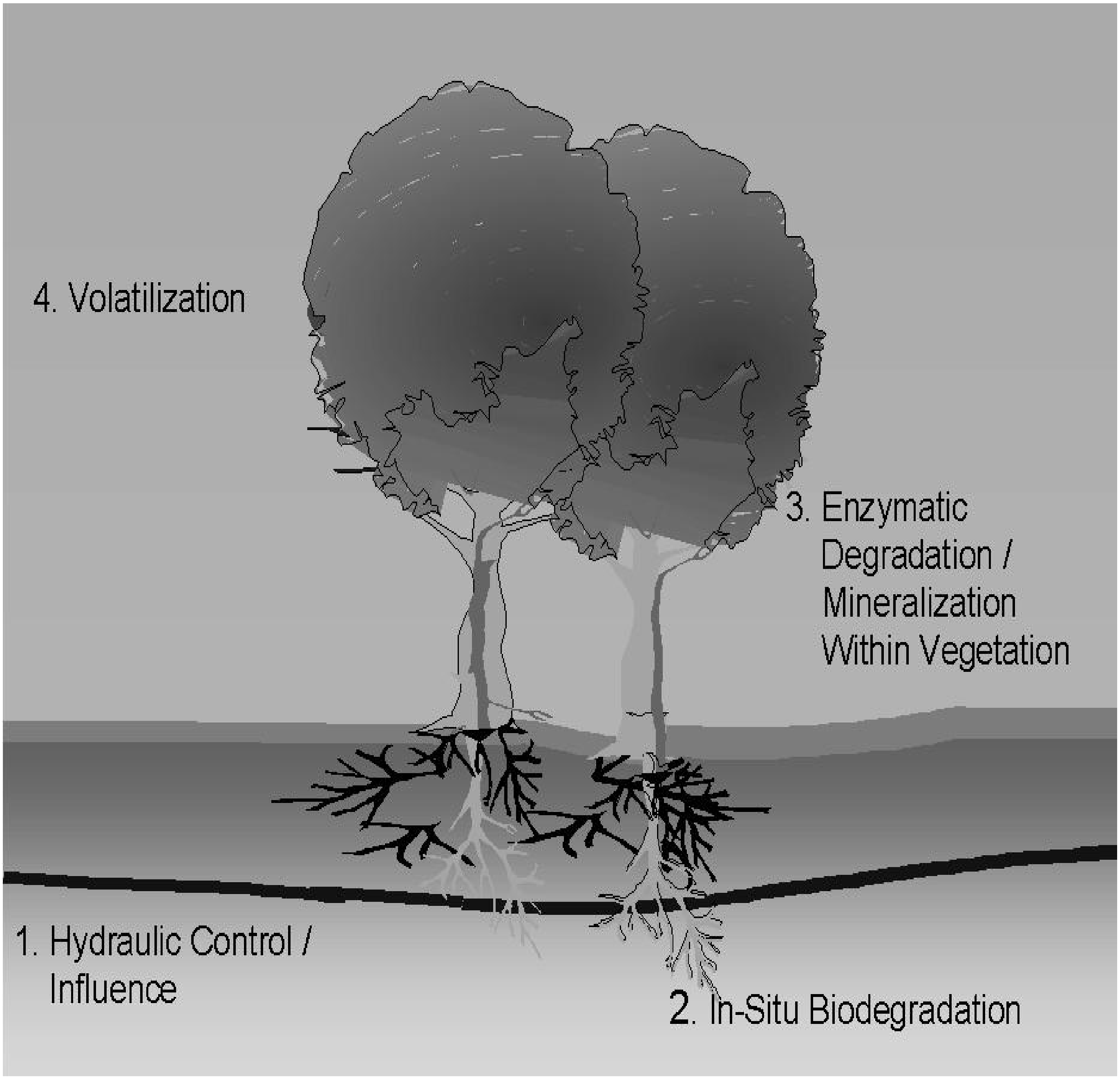

Figure 1-1. Phytoremediation Process Mechanisms

contaminated plume and to possibly flush the aquifer, which is referred to as hydraulic control; and (2) remediation of the contaminated water. In simple terms, plants are biologically based solar-powered pump and treat systems.

The consumptive use of water by phreatophytes, deep rooted plants that can obtain water from a subsurface water source, has historically been considered a liability in some arid and semiarid environments. The consumptive use of water by vegetation, however, is now being viewed differently because of its potential for remediation of contaminated groundwater. Instead of employing energy, capital, and maintenance-intensive pump and treat systems, it may be possible to exploit the natural ability of plants to transpire water. On a hot sunny day the volume of water loss may exceed the total water content of the plant. The success and even the survival of land plants depend on adequate water moving upward from the roots to replace that lost from the canopy by transpiration. Water flow is driven by the difference in free energy of water in the soil and dry air. Accordingly, plants can pump large amounts of water soluble contaminants by means of the transpiration stream.

The amount of transpiration is a function of plant density, leaf area index, radiant solar energy flux, depth to groundwater, temperature, relative humidity and wind speed (Nichols 1994). Roots function as water sensors and grow through the soil following water potentials. When water becomes limited phreatophytes are more resistant to wilting than shallow rooted plants. Trees have the most massive root system of all plants and their root systems are capable of penetrating several meters below the surface (Stomp 1993). Examples of phreatophytic trees are willows, cottonwoods (poplars), salt cedar and mesquite (Fetter 1988).

Plant roots can increase the biological activity in the soil adjacent to the roots; this region in the soil is called the rhizosphere. The rhizosphere consists of both biotic and abiotic parts. Releases from plant roots into the rhizosphere may be inorganic or organic. The carbon in root exudates is from carbon dioxide fixed in the production of carbohydrates. Anywhere from 1 to 40 percent of the net photosynthate may be released from the roots to the soil. Organic rhizosphere exudates take several different forms: simple sugars, amino acids, organic acids, phenolics, and polysaccharides (Shann 1995). The *in situ* function of these exudates has not been fully determined. Tests show they can act as nutrients, as antibiotics, and chemoattractants. Plant roots also affect the soil oxidation-reduction potential by transporting oxygen via the roots or by changing soil porosity. In addition, plants moderate swings in soil water potential through transpiration and by the continual addition of water-retentive organic matter. In essence, the plant-microbe symbiotic relationship can be thought of as being the natural equivalent of a bioreactor that is controlling the environmental conditions and the substances that are required by the microbes for the metabolism of contaminants in the subsurface. By use of solar energy, carbon dioxide, water, and inorganic nutrients, plants provide naturally much of what the bioremediation engineer must supply at a substantial cost (Stomp 1993).

Phreatophytic trees such as eastern cottonwoods (poplars) and willows are rapid growing and in terms of subsurface biomass and transpiration capacity, offer unique opportunities for phytoremediation. Several factors were considered in the selection of eastern cottonwood trees for this demonstration. These factors include extent and rate of root growth, rate of evapotranspiration, ability to assimilate the contaminant(s) of concern, and ability to thrive in the conditions at the site.

1.6 Key Contacts

Additional information on this project and the SITE Program can be obtained from the following sources:

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Information on the SITE Program also is available through the following on-line information clearinghouses:

- The Alternative Treatment Technology Information Center (ATTIC) System is a comprehensive information retrieval system containing data on alternative treatment technologies for hazardous waste including thermal, biological, chemical and physical treatment systems. ATTIC contains several databases that are accessed through a free, public access bulletin board. You may dial into ATTIC via modem at (513) 569-7610. The FTP and Telnet address is cinbbs.cin.epa.gov. The voice help line number is (513) 569-7272.

- The Vendor Information System for Innovative Treatment Technologies (VISITT) is an electronic yellow pages of innovative treatment technologies and vendors. Offered by EPA's Technology Innovation Office, VISITT is a user-friendly database providing data on 325 innovative treatment technologies provided by 204 vendors. VISITT is available for download at http://www.clu-in.org/. For instructions on downloading, installing, and operating VISITT, or submitting information for VISITT, call the help line at (800) 245-4505 or (703) 883-8448.

- The Hazardous Waste Clean-up Information Web Site provides information about innovative treatment technologies to the hazardous waste community. It describes programs, organizations, publications and other tools for federal and state personnel, consulting engineers, technology developers and vendors, remediation contractors, researchers, community groups and individual citizens. CLU-In may be accessed at http://www.clu-in.org/.

Technical reports may be obtained by contacting the Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive in Cincinnati, Ohio, 45268 at (513) 569-7562.

SECTION 2
TECHNOLOGY APPLICATIONS ANALYSIS

This section of the report addresses the general applicability of a phytoremediation system also known as Short Rotation Woody Crop Groundwater Treatment (SRWCGT) that employs hybrid Poplar trees to remove and breakdown organic industrial contaminants in groundwater as well as exert a measure of hydraulic control over the treatment area so as to reduce adverse contaminant migration. This analysis is based in part upon the results of the SITE Program Phytoremediation demonstration conducted at the Carswell Naval Air Station (NAS) Golf Club from April 1996 to September 1998 and research conducted by others.

2.1 Key Features

Phytoremediation is a system that employs hybrid Poplar trees to hydraulically control the migration of contaminated groundwater, as well as biologically enhance the subsurface environment to optimize in-situ reductive dechlorination of the chlorinated ethenes. The SRWCGT system is a low-cost, easy to implement, low-maintenance system that produces virtually no process residuals and requires minimal maintenance. The system is an "evolving" and adaptive process that adjusts to site conditions and increases its effectiveness over time.

Phytoremediation systems represent a broad class of emerging remediation technologies that use plants and their associated rhizospheric microorganisms to remove, degrade, or contain chemical and radioactive contaminants in the soil, sediment, groundwater, surface water and even the atmosphere. Phytoremediation is best described as a solar-energy driven, passive technique that is applicable for the remediation of sites having low to moderate levels of contaminants at shallow depth. Phytoremediation takes advantage of plants' nutrient utilization processes to take in water and nutrients through roots, transpire water through leaves, and act as a transformational system to metabolize organic compounds or absorb and accumulate inorganic compounds. Research has found that certain plants can be used to treat most classes of contaminants, including petroleum hydrocarbons, chlorinated solvents, pesticides, metals, radionuclides, explosives, and excess nutrients. In addition, plants have also shown a capacity to withstand relatively high concentrations of organic chemicals without the types of toxic effects experienced with bioremediation systems. In some cases, plants have demonstrated the ability to uptake and convert chemicals quickly to less toxic metabolites. Depending upon the nature of contamination problems at a site and its particular hydrogeologic setting, plant species are selected based on their following characteristics:

- growth rate and yield,
- evapotranspiration potential,
- production of degradative enzymes,
- depth of root zone,
- contaminant tolerance, and
- bioaccumulation ability.

Despite the fact that most of what is known about this technology is derived from laboratory and small scale field studies, phytoremediation approaches have received higher public acceptance than most conventional remedial options. Phytoremediation systems can be used along with or, in some cases, in place of intrusive mechanical cleanup methods. Plant based remediation systems can function with minimal maintenance once established, generate fewer air and water emissions, generate less secondary waste, leave soil in place and generally are a fraction of the cost incurred for a mechanical treatment approach.

2.2 Operability of the Technology

This discussion on technology operability will focus only on phytoremediation systems that utilize hybrid poplar trees to reduce the mass flux of chlorinated ethenes in shallow groundwater systems through a combination of hydraulic control and in-situ microbially mediated reductive dechlorination. The hybrid Poplar tree system differs little from other phytoremediation approaches in that it basically involves the placement and maintenance of trees in contaminated regions. Tree selection and preparation, method of planting, planting density, distribution and dimensions of tree plots, agronomic inputs, irrigation and maintenance requirements, are highly site specific and vary from site to site and amongst practitioners. Since a phytoremediation approach represents a living remediation system, the planning, installation and maintenance of these systems rely more on the biological and ecological sciences rather than standard engineering practices.

The design, installation, monitoring and maintenance requirements of a phytoremdiation system that employs Poplar trees are highly site-specific, as they are dependent upon the physical, chemical, biological, cultural and regulatory aspects of the site. Factors that affect the operability of a tree-based phytoremediation system include, but are not limited to:

- Hydraulic framework,
- Physical and chemical properties of the soil,
- Distribution and magnitude of contamination,
- Climatic conditions,
- Property characteristics and features, and
- Treatment goals.

A thorough understanding of each of these factors is required to first enable a technology feasibility determination, and secondly, to support decisions on implementability.

As with most sites with environmental problems, it is likely that plenty of information has already been compiled on a site's features and contamination problems. This information, generated by any number or types of investigations, can usually be obtained from the site owner or operator, the appropriate State or Federal regulatory agency overseeing activities at the site, the local government (engineering, public works, health department), municipal or county library, private consultants and well drilling firms. Despite the volumes of information that may already be available on a candidate phytoremediation site, it is still typically necessary to perform a series of limited, yet highly specific studies to better assist with design decisions, to establish appropriate site preparation methods and to determine maintenance tasks and schedules.

An understanding of the hydraulic framework of a site relies on developing and integrating the following hydrogeologic aspects for the site:

- groundwater flow direction,
- hydraulic gradient,
- connectivity of water bearing zones,
- identification of primary groundwater flow pathways,
- principal mechanism of groundwater flow (intergranular or secondary porosity features),
- average depth to groundwater,
- seasonal and diurnal groundwater level fluctuations,
- aquifer recharge points,
- interrelation of the contaminated aquifer with other aquifers or surface water features,
- aquifer thickness,
- groundwater velocity,
- volume of groundwater that flows through the proposed treatment area
- volume of groundwater stored in the aquifer beneath the proposed treatment area
- size and shape of the contaminant plume.

An understanding of the hydraulic setting is necessary for determining whether this technology is feasible at a site. It may be discovered after evaluating certain hydraulic parameters that the contaminated aquifer is too deep, beyond the reach of the hybrid Poplar tree roots. It may also be discovered that groundwater flow beneath the proposed treatment area is in excess of what could possibly be attenuated through some combination of hydraulic control and in-situ biologically mediated reductive dechlorination.

An understanding of the hydrogeologic setting beneath a site is important. Many practitioners base most of their design considerations solely upon the hydraulic constraints of a tree-based phytoremediation system. These design considerations include:

- planting density (i.e., tree spacing),
- plot dimensions and orientation,
- number of plots needed, and
- arrangement of these plots across the site.

An effective tree-based phytoremdiation system is dependent upon the collective effort of numerous trees evenly spaced in a series of plots. A tree-based phytoremediation system is therefore land intensive, requiring plenty of clear space, or at least enough for all the trees that can be grown in a given area to do the job. It is therefore important to identify, and if economically feasible, eliminate any obstacles or restrictive features on a property that might hamper the effectiveness of a tree-based phytoremediation system. In order for the system to be effective the site should be cleared of any above or below ground obstructions that might interfere with the establishment and health of the tree plots.

Tree stands or plantations are oriented so that the long sides of the stands are generally perpendicular to the direction of groundwater flow (See Figure 4-1). The long sides of the plantations generally span the most concentrated portion of the contaminant plume. Individual trees are planted in a series of rows. Tree spacing within these rows is up to the discretion of the practitioner and is determined on how quickly the practitioner wants to achieve maximum stand-level transpiration rates. Trees are generally planted between 1.5 m to 2.5 m apart.

Although research has shown that hydraulic control is the principle mechanism responsible for reductions in the mass flux of contamination transported across the planted area during the early stages of tree-based treatment, other mechanisms, especially microbially mediated reductive dechlorination may become just as prominent after the third or forth season. Reductive dechlorination would become the most important mechanism operating during the dormant season. Therefore, applicability and design decisions should not be based entirely on the ability of the system to achieve hydraulic capture. Such decisions could prove to be costly, resulting in either more and/or larger tree plots than are necessary, or the disqualification of a tree-based phytoremediation system as a viable alternative for the site. Hydraulic capture may not be possible or even practical at some sites, yet the desired reduction in contaminant mass flux might still be achieved through some combination of the other phytoremediation mechanisms. A discussion of these mechanisms is presented in Section 4.0 of this report.

Before designing any remediation system, and the same holds true for a tree-based phytoremediation system, it is important to understand the treatment goals that have been set for the site. Certain goals may be based upon a specific soil and/or groundwater cleanup criteria or based upon a site receptor risk. Remediation goals may require source removal or source control. Each of these goals implies potentially different design considerations and factors into the overall treatment period.

Another important aspect to remember when designing a tree-based phytoremediation technology is that the system is a dynamic one and is capable of changing and adapting to particular site conditions. In areas characterized by heterogenous hydraulic conditions, trees have been observed to thin themselves or increase their size based upon their access to groundwater. This is especially evident with hydrogeologic settings characterized by preferential groundwater flow pathways (e.g., buried stream channels).

Prevailing hydraulic conditions at a site generally determine the time it takes for the trees to begin exerting an influence on the groundwater system. Shallower groundwater systems would be more readily available to the tree roots, requiring less time for the system to begin affecting changes in the groundwater. Special planting techniques may be implemented for an application on deeper aquifers in order to speed up the time it normally takes for the roots to reach the contaminated aquifer.

An understanding of the physical and chemical properties of a site's soil is important in knowing what adjustments need to be made to the soil to foster healthy tree growth, and in particular, vigorous root growth. The condition of a site's soils will also be a factor in deciding upon the appropriate tree planting procedures. The soil in a proposed plot area might have to be reworked by plowing and discing appropriate mixtures of fertilizer and amendments (i.e., organic matter, drainage-enhancing media) into the upper portions of the soil profile. Special rooting mixtures of fertilizers, organic-rich soil, native soil and other amendments may have to be formulated and placed into the tree boreholes or trenches during planting. Soil moisture retention, soil moisture profiles, drainage and infiltration rates factor into decisions regarding the necessity of an irrigation system or some type of ground cover (i.e., grass, legumes). An irrigation system might be necessary during the first few growing seasons to provide the trees with water until the roots reach the groundwater table. It may also be necessary to install a ground cover to make the trees less reliant on rainfall infiltration and force them to seek out the aquifer as a source of water.

Understanding the distribution and magnitude of contamination at a site is important for the proper placement and dimensions of the tree plots and selection of a tree type that has a natural tolerance to the levels of contamination it will encounter at the site. To ensure optimal positioning of the plots, it is important to pinpoint contaminant source areas, discern historical contamination patterns and activities that led to those patterns at the site, establish concentration gradients in both the soil and groundwater and determine the plume boundaries. Groundwater contaminants can be treated significantly downgradient of the source through tree induced enhanced bioremediation. Ideally, the phytoremediation plots should be positioned perpendicular to the path of migrating contamination and straddle an upgradient portion of the plume. This is also the approach that should be taken for a treatment strategy intended to limit adverse contaminant migration away from the site.

If the intent is to utilize the trees for enhanced bioremediation of the soil contaminants, then care should be taken to position the tree plots over the contaminant source areas. The trees would then be in position to take up the contaminants where they would be transpired or metabolized through enzymatic reactions in the tissue of the tree, or broken down in the rhizosphere as a consequence of enhanced microbial activity due to the release of exudates and enzymes by the tree roots.

Climatic conditions at a site need to be evaluated with regard to selecting appropriate tree type, determining the arrangement and size of the plantations, and assessing the need for an irrigation system. Generally, the trees should be obtained locally, to ensure that the hybrid variation is well adapted to the local climate and less susceptible to disease. The geographical location of the site dictates the length of the growing season (i.e., the time when the trees actively transpire water from the contaminated aquifer). One can expect longer growing seasons in the lower latitude regions as opposed to higher latitude regions. Regardless of the geographic location, each site will experience a dormant period when the trees stop pumping groundwater. During these dormant cycles, microbial mediated reductive dechlorination becomes the dominant remedial mechanism. Regions characterized by hot and dry summers might need to operate a drip irrigation system during the first few growing seasons until the tree roots extend down to the aquifer.

2.3 Applicable Wastes

Tree-based phytoremediation systems operate through a process of phytotransformation, which involves the uptake of organic and nutrient contaminants from the soil and groundwater by the tree's roots, followed by the breakdown of these compounds in the tissue of the tree (Schnoor, 1997). The direct uptake of organics by trees has been found to be a surprisingly efficient removal mechanism at sites contaminated at shallow depth with moderately hydrophobic organic chemicals (octanol-water partition coefficients, log K_{ow} = 1 to 3.5).

A tree-based phytoremediation system is applicable to sites where the principal soil and groundwater contaminants consist of benzene, toluene, ethylbenzene and xylenes (BTEX), chlorinated organics and short-chain aliphatic compounds. Given this list of chemicals, a tree-based phytoremediation system may be applicable at the following waste sites: Petrochemical sites, ammunition waste sites, fuel spills, chlorinated solvent plumes, landfill leachates and agricultural chemicals (pesticides and fertilizers).

2.4 Availability and Transportability of the Equipment

Unlike a traditional remediation system, a tree-based phytoremediation system is a living remediation technology that does not have any equipment requirements other than those which are necessary to install, maintain and monitor such a system. Tree-based phytoremediation systems are highly site specific in-situ approaches and are not considered transportable. The working components of a tree-based phytoremdiation system are the roots, stems and leaves of the trees. The trees for this type of system can usually be obtained locally from a nursery or tree farm. Trees would be delivered to the site via flat-bed truck. Equipment required to install the system is entirely site specific, and to a large extent, dependent upon the soil conditions, depth to which the trees need to be planted, and the size of the plots. Trenching equipment was used to install the SRWCGT system at the Carswell NAS. The practitioner might choose to out source any ripping (Florida Forestry Information, accessed September 2001, at URL http://www.sfrc.ufl.edu/Extension/ffws/home.htm), trenching, or borehole drilling deemed necessary to establish the tree plots to a local agricultural land preparation company, construction firm, or well drilling firm that has the specialized equipment and experience to perform this work. These construction and well drilling firms may also be called upon to install portions of the monitoring system, which may include the installation of monitoring wells, peizometers, soil moisture sensors, and soil borings. Other equipment that might be necessary during any ground preparation activities may include a backhoe, front-end loader and skid mounted loader for moving fertilizer, top soil and fill around the site, a mixing unit and a screen for formulating the root mix, a trencher for burying data cables and irrigation pipe, and discing and plowing equipment for loosening up the ground and mixing in fertilizer and soil conditioners. All of this equipment can be obtained locally and is usually available for rent. Equipment for an irrigation system can usually be obtained from a local plumbing supplier or home center. There is a considerable amount of equipment available for monitoring a tree-based phytoremediation system, and there is considerable variation in sophistication and cost. Much of this equipment can be obtained from companies that specialize in products (i.e., plant bio-sensors, tree transpiration measurements, plant bio-productivity and environmental conditions) that support the agricultural community.

Typical monitoring equipment for tree-based phytoremediation systems includes a network of monitoring wells. Water levels in monitoring wells provide a direct means for assessing groundwater uptake by the trees. These wells can be equipped with electronic pressure transducers connected to data loggers for continuous water level monitoring. Soil moisture sensors can be arrayed across the site and installed at various depths to track changes in soil moisture as a function of root mass development. Soil moisture data can be collected on data loggers and used for decisions on when to irrigate. Weather stations are often installed and the data collected by them is used in conjunction with sap flow measurements to estimate tree transpiration rates.

2.5 Materials Handling Requirements

A tree-based phytoremediation system does have some materials handling requirements, especially during the installation phase. Depending upon soil conditions, tree plot areas might require plowing, tilling, and discing to facilitate fertilizer infiltration, increase soil porosity, ease planting and foster vigorous root growth. The equipment needed to do this can usually be rented locally. Depending upon the tree planting requirements for a site, the proposed plots may have to be ripped or trenched, or boreholes may have to be drilled. Ripping can be contracted out to an agricultural land preparation company. Trenching equipment can usually be obtained locally. A subcontract arrangement is typically needed for the drilling of any boreholes. Fertilizer and soil conditioners may have to be mixed into the soil or used to formulate specialized root mixtures that will be placed in the boreholes or trenches at the time the trees are planted. Fertilizer and soil conditioning components could include any variety of commercial fertilizer mixes depending on the desired nitrogen/phosphorus/potassium (N/P/K) ratios. Soil conditioning materials have traditionally included organic carbon, aged manure, sewage sludge, compost, straw and mulch. A mix mill/grinder and spreader might be needed for handling the fertilizer and various soil conditioners. Screening equipment (i.e., subsurface combs, portable vibrating screens) may also be necessary to remove debris and cobbles from the soil and to remove debris from soil conditioning material.

In addition to a drill rig and some of the agricultural equipment mentioned, a tree-based phytoremediation system normally requires an assortment of heavy equipment during the installation phase. Excavators, back-hoes and trenchers are needed to create trenches for planting tree rows and for laying irrigation piping and data cables. Dump trucks and front-end loaders would be required for delivering and/or moving soil and soil conditioners around the site. Flat-bed trucks might be required for delivering trees, seed, fertilizer and other supplies. Graders and scrappers would be used for re-leveling the ground surface after tree installation. Fork lifts would be used for moving pallets and waste drums around the site.

Contaminated soil would require specialized handling, storage and disposal requirements. Soil may have to be kept damp when being reworked to limit dust production. Contaminated drill cuttings usually have to be containerized (usually in 55-gallon drums) and disposed of at a permitted disposal facility. Contaminated soil could be generated during any drilling and excavation activities.

As many as 1,000 to 2,000 trees per acre may be initially planted to assure a significant amount of evapotranspiration in the first few years. The trees will naturally thin themselves through competition to 600 to 800 trees per acre over the first six years. In order to off-set some of the costs associated with this remediation technology, the trees can be harvested on a six-year rotation and sold for fuelwood or pulp and paper. The trees will grow back from the cut-stump.

2.6 Site Support Requirements

Phytoremediation systems in general have minimal site support requirements. Typically, these systems require few utilities to operate. Water is generally needed for irrigation and possibly decontamination purposes. A drip irrigation system may be installed and operated periodically over the first few growing seasons when the young trees are most susceptible to water stress problems. It may be operated at times afterwards to make up for rainfall deficits that occur during times of drought. Irrigation water would not necessarily have to be potable water. Depending upon local regulations, water from the contaminated aquifer might be used at no cost, with the additional benefit of enhancing groundwater treatment during the first few growing seasons when little remediation is expected. The electricity needed to operate well pumps can be provided by small generators. Monitoring equipment (e.g., soil moisture probes, pressure transducers, data loggers, weather station components) can be powered by batteries or solar panels.

Depending upon site location, security measures might be required to protect the public from accidental exposures and prevent accidental and intentional damage to the trees and monitoring equipment. A fence would also serve the purpose of discouraging local wildlife from using the trees as a food source (i.e., deer, beavers).

2.7 Range of Suitable Site Characteristics

Tree-based phytoremediation is best applied to sites with relatively shallow soil and groundwater contamination. The contaminants can be organic or inorganic, but should possess certain physical and chemical properties that make them amenable to phytotransformation, rhizosphere bioremediation, and phytoextraction. This technology is well suited for use at very large field sites where other methods of remediation are not cost-effective or practical. It is also best utilized at sites with low concentrations of contaminants where the remediation objectives for the site are consistent with a long-term contaminant reduction strategy. Sites should have plenty of open space, and be clear of man-made structures; existing vegetation can be left intact.

2.8 Limitations of the Technology

Research and data from various field demonstrations have shown that tree-based phytoremediation systems are a promising, cost-effective and aesthetically pleasing remediation alternative that has been successfully applied at a number of sites. Unfortunately, many of these applications have been at small sites, where few funds are available for long-term compliance monitoring. Long-term monitoring and evaluation of tree-based phytoremediation technologies is needed to demonstrate system effectiveness and better define phytoremediation mechanisms. Although current research continues to explore and push the boundaries of phytoremediation applications, there are some limiting factors that need to be considered.

Contaminant to root contact, a function of root depth and mass, is a limiting factor for direct uptake of contaminants into the tree, but not for enhanced reductive dechlorination processes. While most phytoremediation systems are limited to the upper 3 meters of the soil column, research and SITE Program experience suggests that hybrid Poplar systems may be effective to depths greater than 8 meters. Systems that utilize other tree species may be effective to even greater depths. To overcome these depth barriers, researchers and companies that offer phytoremediation services have developed and employed specialized (often proprietary) techniques that train the tree roots to penetrate to greater depths, or herd them into deeper contamination zones through the use of subsurface drip irrigation. Deeper zones of contamination can possibly be treated through a process of pumping the contaminated groundwater to the surface and applying it to the plantations through drip irrigation. On the other hand, enhanced reductive dechlorination is more dependent on the availability of dissolved organic carbon in the groundwater, which is typically increased in the soil water and groundwater beneath the tree stands.

Contamination that is too tightly bound to the organic portions of a soil and root surfaces may also pose limitations on the effectiveness of this technology. This is especially true with hydrophobic compounds ($\log K_{ow} > 3.5$), which due to their octanol-water partition coefficients, cannot be easily translocated within the tree or are simply unavailable to microorganisms in the rhizosphere. On the other hand, contaminants that are too water soluble ($\log K_{ow}$ <1.0) are not sufficiently sorbed to roots nor actively transported through plant membranes. These contaminants would simply pass through the roots unimpeded.

Another limiting factor is that tree-based phytoremediation may require more time to achieve cleanup standards than other more costly treatment alternatives, such as excavation, landfilling, or incineration. A tree-based phytoremediation system may take ten plus years to completely remediate a site. This type of Phytoremediation system is limited by the growth rate of the trees. Depending upon the depth to groundwater, the length of growing season and tree type, it may take two or more growing seasons before the trees start to exert a hydraulic effect on the contaminated aquifer and even longer before microbial mediated reductive dechlorination becomes a viable mechanism. In addition, removal and degradation of organics in contaminated matrices is likely limited by mass transfer. The desorption and mass transport of chemicals from soil particles to the aqueous phase may therefore become a rate limiting step.

Tree-based phytoremediation systems may not be the most suitable remediation technique for sites that pose acute risks for human and other ecological receptors. Although trees have shown a remarkable tolerance to contaminant levels often considered too toxic for bioremediation approaches, very high concentrations of organics may actually inhibit tree growth, thus limiting the application of this technology at some sites or portions of sites (Dietz and Schnoor, 2001). Sites that possess phytotoxic levels of organic contamination and pose acute exposure risks are best handled by first applying a faster, more expensive ex-situ technique. A tree-based phytoremediation system can then serve as a final polishing step to close the site after other clean-up technologies have been used to treat the hot spots.

Practitioners of tree-based phytoremediation still need to better document the fate of organic contaminants in tree tissue, establish whether contaminants can collect in leaves and be released during litter fall, or accumulate in fuel wood or mulch.

There has been some concern over the potential of ecological exposures whenever plants are used to interact with contaminants. Of course this threat is more obvious and better understood for plants used for the purpose of extracting and accumulating heavy metals and radionuclides. Unlike metals, some research has shown that most organic contaminants do not accumulate in significant amounts in plant tissue. Nonetheless, if some organisms (e.g., caterpillars, rodents, birds, deer, etc.) seem likely to ingest significant amounts of the vegetation, and if harmful bioconcentration up the food chain is a concern during the life of the remediation effort, appropriate exposure control measures should be implemented including perimeter fencing, overhead netting, and pre-flowering harvesting.

Another issue that might be a limiting factor from a regulatory standpoint is the transfer of the contaminants or metabolites to the atmosphere. A number of studies have been conducted to determine if organic contaminants, such as TCE, simply pass through the trees and are released to the atmosphere through leaf stomata during evapotranspiration. Research in this area has produced mixed results and is not close to quantifying the amounts of organics released. According to some studies, transpiration of TCE to the atmosphere has been measured (Newman et al. 1997), but little information is available that indicates any release of more toxic daughter products (i.e., vinyl chloride). The same researcher has shown that a series of aerobic transformations occur whereby some of the TCE is transformed to trichloroethanol, trichloroacetic acid, and dichloroacetic acid by hybrid Poplar trees.

2.9 Technology Performance Versus Arars

Under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA), remedial actions undertaken at Superfund sites must comply with federal and state (if more stringent) environmental laws that are determined to be applicable or relevant and appropriate requirements (ARARs). ARARs are determined on a site-specific basis by the remedial project manager. They are used as a tool to guide the remedial project manager toward the most environmentally safe way to manage remediation activities. The remedial project manager reviews each federal environmental law and determines if it is applicable. If the law is not applicable, then the determination must be made whether the law is relevant and appropriate.

This subsection discusses specific federal environmental regulations pertinent to the operation of tree-based phytoremediation systems, including the transport, treatment, storage and disposal of wastes and treatment residuals. Federal and state ARARs are presented in Table 2-1. These regulations are reviewed with respect to the demonstration results. State and local requirements, which may be more stringent, must also be addressed by remedial project managers.

2.9.1 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The CERCLA of 1980 as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986 provides for federal funding to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or to the environment. As part of the requirements of CERCLA, the EPA has prepared the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) for hazardous substance response. The NCP is codified in Title 40 Code of Federal Regulations (CFR) Part 300, and delineates the methods and criteria used to determine the appropriate extent of removal and cleanup for hazardous waste contamination.

SARA states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It directs EPA to do the following:

- Use remedial alternatives that permanently and significantly reduce the volume, toxicity, or the mobility of hazardous substances, pollutants, or contaminants;
- Select remedial actions that protect human health and the environment, are cost-effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent possible; and
- Avoid off-site transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist [Section 121(b)].

The Carswell NAS demonstration site is part of a Superfund site (Air Force Plant No. 4) ; therefore, CERCLA/SARA is relevant and appropriate for the treatment technology occurring on-site. The phytoremediation system at the Carswell site meets most of the SARA criteria. It is an *in situ* treatment technology, thus the treatment process occurred in place and the removal of the contamination is permanent and protective to human health and the environment; the volume and mobility of halogenated organics in the soil and groundwater is reduced to help prevent the migration of contamination off-site or to uncontaminated water supplies; phytoremediation reduces the toxicity of the treated waste media (soil or groundwater); and phytoremediation is cost-effective and an alternative treatment technology.

In general, two types of responses are possible under CERCLA: removal and remedial action. Superfund removal actions are conducted in response to an immediate threat caused by a release of a hazardous substance. Many removals involve small quantities of waste of immediate threat requiring quick action to alleviate the hazard. Remedial actions are governed by the SARA amendments to CERCLA. As stated above, these amendments promote remedies that permanently reduce the volume, toxicity, and mobility of hazardous substances or pollutants. The tree-based phytoremediation system is likely to be part of a CERCLA remedial action. Remedial actions are governed by the SARA amendments to CERCLA.

On-site remedial actions must comply with federal and more stringent state ARARs. ARARs are determined on a site-by-site basis and may be waived under six conditions: (1) the action is an interim measure, and the ARAR will be met at completion; (2) compliance with the ARAR would pose a greater risk to health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method; (5) a state ARAR has not been consistently applied elsewhere; and (6) ARAR compliance would not provide a balance between the protection achieved at a particular site and demands on the Superfund for other sites. These waiver options apply only to Superfund actions taken on-site, and justification for the waiver must be clearly demonstrated.

2.9.2 Resource Conservation and Recovery Act (RCRA)

RCRA, an amendment to the Solid Waste Disposal Act (SWDA), is the primary federal legislation governing hazardous waste activities. It was passed in 1976 to address the problem of how to safely dispose of the enormous volume of municipal and industrial solid waste generated annually. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are also applicable to CERCLA activities. The Hazardous and Solid Waste Amendments (HSWA) of 1984 greatly expanded the scope and requirements of RCRA.

RCRA regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. These regulations are only applicable to the tree-based phytoremediation system if RCRA-defined hazardous wastes are present. If soils are determined to be hazardous according to RCRA (either because of a characteristic or a listing carried by the waste), essentially all RCRA requirements regarding the management and disposal of this hazardous waste will need to be addressed

Table 2-1. Federal and State Applicable and Relevant and Appropriate Requirements (ARARs) for the Tree-Based Phytoremediation System

Process Activity	ARAR	Description	Comment
Characterization of untreated waste	RCRA: 40 CFR 261 (or State Equivalent)	Untreated waste should be characterized to determine if it is a hazardous waste, and if so, if it is a RCRA-listed waste.	Applicable. Perform chemical and physical analyses.
Drilling and excavation activities related to system installation	OSHA: 29 CFR 1910.120	Personnel need to be protected from volatile emissions and airborne particulates during soil boring and excavation activities. Personnel need to be provided with protective equipment and be involved in a medical monitoring program.	Provide air monitoring equipment during drilling; Provide personal protection equipment as necessary.
Waste processing using Tree-Based Phytoremediation technology	RCRA: 40 CFR 264 Subpart J and 270 (or State Equivalent)	Treatment of a RCRA hazardous waste requires a permit. If non-RCRA waste, then a permit or a variance from the State hazardous waste agency may be required.	If activity is conducted within a one year time period,a full RCRA permit may not be required.
Cleanup standards are established	SARA Section 121(d)(2)(A)(ii); SDWA: 40 CFR 141	Remedial actions of surface and groundwater are required to meet MCLGs (or MCLs) established under SDWA.	Applicable for surface and groundwater; Relevant and appropriate if drinking water source could be affected.
	SARA Section 121(d)(2)(A)	Site-specific Remediation Goals can be established through the Record of Decision (ROD). Remediation Goals may be developed during treatability work for treatment of soil.	Applicable, relevant and appropriate.
Storage of waste	RCRA: 40 CFR Part 264 Subpart J (or State Equivalent)	Storage tanks for recovered liquid waste must be placarded appropriately, have secondary containment, and be inspected daily.	If storing non-RCRA wastes, RCRA requirements are still relevant and appropriate.
	RCRA: 40 CFR Part 264 Subpart I (or State Equivalent)	Containers of contaminated soil from tree borings and excavation activities need to be labeled as a hazardous waste, the storage area needs to be in good condition, weekly inspections should be conducted, and storage should not exceed 90 days unless a storage permit is acquired.	Applicable for RCRA wastes; relevant and appropriate for non-RCRA wastes.

Table 2-1 (Cont'd). Federal and State Applicable and Relevant and Appropriate Requirements (ARARs) for the Tree-Based Phytoremediation System

Process Activity	ARAR	Description	Comment
Waste Disposal	RCRA: 40 CFR Part 262; SARA Section 121 (d)(3)	Generators of hazardous waste must dispose of the waste at a facility permitted to handle the waste. Wastes generated include soil cuttings and recovered liquid waste. Generators must obtain an EPA ID No. prior to waste disposal.	Applicable: Wastes generated by Tree-Based Phytoremediation is limited to soil cuttings generated during tree installation activities. Purge water generated during groundwater sampling activities might constitute another waste.
	CWA: 40 CFR Parts 403 and/or 122 and 125	Discharges of non-hazardous wastewater to a POTW must meet pre-treatment standards; discharges to a navigable water must be permitted under NPDES.	Applicable and appropriate for decontamination rinsates.
	SDWA: 40 CFR Parts 144 and 145	Specifies standards that apply to the disposal of contaminated wastewater in underground injection wells. Permission must be obtained from U.S. EPA to use existing permitted underground injection wells or to construct and operate new wells.	Applicable if underground injection is selected as a disposal means for contaminated wastewater.
	RCRA: 40 CFR Part 262 and 263 (or State Equivalent)	Hazardous wastes transported off-site for treatment or disposal must be accompanied by a hazardous waste manifest, and must meet packaging and labeling requirements. Hazardous waste haulers must be EPA-licensed.	Applicable
	RCRA: 40 CFR Part 268	Hazardous wastes must meet specific treatment standards prior to land disposal, or must be treated using specific technologies.	Applicable

by the remedial managers. Wastes defined as hazardous under RCRA include characteristic and listed wastes. Criteria for identifying characteristic hazardous wastes are included in 40 CFR Part 261 Subpart C. Listed wastes from specific and nonspecific industrial sources, off-specification products, spill cleanups, and other industrial sources are itemized in 40 CFR Part 261 Subpart D. RCRA regulations do not apply to sites where RCRA-defined wastes are not present.

Unless they are specifically delisted through delisting procedures, hazardous wastes listed in 40 CFR Part 261 Subpart D currently remain listed wastes regardless of the treatment they may undergo and regardless of the final contamination levels in the resulting effluent streams and residues. This implies that even after remediation, treated wastes are still classified as hazardous wastes because the pre-treatment material was a listed waste.

For generation of any hazardous waste, the site responsible party must obtain an EPA identification number. Other applicable RCRA requirements may include a Uniform Hazardous Waste Manifest (if the waste is transported off-site), restrictions on placing the waste in land disposal units, time limits on accumulating waste, and permits for storing the waste.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR Part 264, Subpart F (promulgated) and Subpart S (partially promulgated). These subparts also generally apply to remediation at Superfund sites. Subparts F and S include requirements for initiating and conducting RCRA corrective action, remediating groundwater, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements may be waived for temporary treatment units operating at corrective action sites and provides information regarding requirements for modifying permits to adequately describe the subject treatment unit.

2.9.3 Clean Air Act (CAA)

The CAA establishes national primary and secondary ambient air quality standards for sulfur oxides, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead. It also limits the emission of 189 listed hazardous pollutants such as vinyl chloride, arsenic, asbestos and benzene. States are responsible for enforcing the CAA. To assist in this, Air Quality Control Regions (AQCR) were established. Allowable emission limits are determined by the AQCR, or its sub-unit, the Air Quality Management District (AQMD). These emission limits are based on whether or not the region is currently within attainment for National Ambient Air Quality Standards (NAAQS).

The CAA requires that treatment, storage, and disposal facilities comply with primary and secondary ambient air quality standards. Fugitive emissions from the tree-based phytoremediation system may come from (1) soil conditioning and borehole drilling activities and (2) periodic sampling activities. Soil moisture should be managed during system installation to prevent or minimize the impact from fugitive emissions. Although rhizospheric biodegradation and breakdown of chemicals through metabolic activities within plant tissue are components of phytoremediation, these processes as they relate to this technology are not well understood. There is some concern that organic contaminants are only partially broken down, implying that an unknown portion of the original contaminants and its daughter products may be released to the atmosphere during evapotranspiration.

No air permits are required for the tree-based phytoremediation system operated at the Carswell NAS Golf Club.

2.9.4 Clean Water Act (CWA)

The objective of the Clean Water Act is to restore and maintain the chemical, physical and biological integrity of the nation's waters by establishing federal, state, and local discharge standards. If treated water is discharged to surface water bodies or Publicly Owned Treatment Works (POTW), CWA regulations will apply. A facility desiring to discharge water to a navigable waterway must apply for a permit under the National Pollutant Discharge Elimination System (NPDES). When a NPDES permit is issued, it includes waste discharge requirements. Discharges to POTWs also must comply with general pretreatment regulations outlined in 40CFR Part 403, as well as other applicable state and local administrative and substantive requirements.

Other than the tree’s capacity to pump groundwater, phytoremediation technologies generally do not involve the mechanical pumping, treatment and discharge of surface/groundwater. In a few rare cases where contaminated groundwater occurs at depth, mechanical pumping might be used to bring the water to the surface where it would then be applied to the plants via drip irrigation. Since this water technically would not be discharged to a navigable waterway, it is unlikely that a NPDES permit will apply.

2.9.5 Safe Drinking Water Act (SDWA)

The SDWA of 1974, as most recently amended by the Safe Drinking Water Amendments of 1986, requires the EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorized national drinking water standards and a joint federal-state system for ensuring compliance with these standards.

The National Primary Drinking Water Standards are found in 40 CFR Parts 141 through 149. These drinking water standards are expressed as maximum contaminant levels (MCLs) for some constituents, and maximum contaminant level goals (MCLGs) for others. Under CERCLA (Section 121 (d) (2) (A) (ii)), remedial actions are required to meet the standards of the MCLGs when relevant. Since a tree-based phytoremediation system is considered a groundwater remediation system, it is likely that these standards would be applicable.

Parts 144 and 145 discuss requirements associated with the underground injection of contaminated water. If processing pumped contaminated groundwater through the plantation's drip irrigation system is an option, approval from EPA for constructing and operating this phytoremediation system in this mode will be required.

2.9.6 Toxic Substances Control Act (TSCA)

The TSCA of 1976 Grants the U.S. EPA authority to prohibit or control the manufacturing, importing, processing, use, and disposal of any chemical substance that presents an unreasonable risk of injury to human health or the environment. These regulations may be found in 40 CFR Part 761; Section 6(e) deals specifically with PCBs. Materials with less than 50 ppm PCB are classified as non-PCB; those containing between 50 and 500 ppm are classified as PCB-contaminated; and those with 500 ppm PCB or greater are classified as PCB. PCB-contaminated materials may be disposed of in TSCA-permitted landfills or destroyed by incineration at a TSCA-approved incinerator; PCBs must be incinerated. Sites where spills of PCB-contaminated material or PCBs have occurred after May 4, 1987 must be addressed under the PCB Spill Cleanup Policy in 40 CFR Part 761, Subpart G. The policy establishes cleanup protocols for addressing such releases based upon the volume and concentration of the spilled material. There is little if any documentation supporting tree-based phytoremediation as a viable option in the remediation of PCBs. The properties of PCBs do not make it amenable for direct uptake by the roots of the trees. It is however possible that enhanced rhizospheric bioremediation may be capable of breaking down some PCB congeners.

2.9.7 Occupational Safety and Health Administration (OSHA) Requirements

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with the OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provides for the health and safety of workers at hazardous waste sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of OSHA, which describes safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, must also be met.

All technicians involved with the construction and operation of a tree-based phytoremediation system may be required to have completed an OSHA training course and be familiar with all OSHA requirements relevant to hazardous waste sites. Workers on hazardous waste sites must also be enrolled in a medical monitoring program. The elements of any acceptable program must include: (1) a health history, (2) an initial exam before hazardous waste work starts to establish fitness for duty and as a medical baseline, (3) periodic examinations (usually annual) to determine whether changes due to exposure may have occurred and to ensure continued fitness for the job, (4) appropriate medical examinations after a suspected or known overexposure, and (5) an examination at termination.

For most sites, minimum PPE for workers will include gloves, hard hats, steel-toe boots, and Tyvek® coveralls. Depending on contaminant types and concentrations, additional PPE may be required, including the use of air purifying respirators or supplied air. Noise levels are not expected to be high, except during the ground preparation and tree planting phase which will involve the operation of heavy equipment. During these activities, noise levels should be monitored to ensure that workers are not exposed to noise levels above a time-weighted average of 85 decibels over an eight-hour day. If noise levels increase above this limit, then workers will be required to wear hearing protection. The levels of noise anticipated are not expected to adversely affect the community, but this will depend on proximity to the treatment site.

2.9.8 State Requirements

State and local regulatory agencies may require permits prior to the operation of a tree-based phytoremediation system. Most federal permits will be issued by the authorized state agency. If, for example, the contaminated drill cutting waste is considered a RCRA waste, a permit issued by the state may be required to operate the system as a treatment, storage, and disposal (TSD) facility. The state may also require a TSD permit for on-site storage greater than 90 days of hazardous waste. An air permit issued by the state Air Quality Control Region may be required if air emissions in excess of regulatory criteria, or of toxic concern, are anticipated. Local state agencies will have direct regulatory responsibility for environmental media issues. If remediation is at a Superfund site, federal agencies, primarily the U.S. EPA, will provide regulatory oversight. If off-site disposal of contaminated waste is required, the waste must be taken to the disposal facility by a licensed transporter.

SECTION 3
ECONOMIC ANALYSIS

3.1 Introduction

The costs associated with applying a Short Rotation Woody Crop Groundwater Treatment (SRWCGT)System as an option for the remediation of halogenated hydrocarbons in shallow groundwater systems and the hydraulic control of contaminant migration have been broken out and discussed under the 12 cost categories that reflect typical cleanup activities performed at Superfund sites:

(1) Site Preparation;
(2) Permitting and Regulatory Requirements;
(3) Capital Equipment;
(4) Start-up and Fixed Costs;
(5) Labor;
(6) Consumables and Supplies;
(7) Utilities;
(8) Effluent Treatment and Disposal;
(9) Residual Waste Shipping, Handling, and Disposal Costs;
(10) Analytical Services;
(11) Maintenance and Modifications; and
(12) Demobilization.

The primary purpose of this economic analysis is to provide a cost estimate for a commercial application of a SRWCGT system using Poplar trees. This analysis is based on the assumptions and costs provided by U.S. Air Force project personnel, and on the results and experiences gained from a 3-year SITE demonstration of the process on a TCE contaminated shallow aquifer at the Carswell Naval Air Station (NAS) Golf Club, Fort Worth, Texas. Table 3-1 presents the costs for an application at a 200,000-ft^2 (~4.6 Acres) hypothetical model site. When appropriate and relevant, some of the cost figures for the model site were derived from actual costs and design criteria used for the Carswell NAS Golf Club system. These costs and design criteria were then applied to a hypothetical set of hydraulic and chemical conditions at the model site. The costs listed in each of the 12 categories for the model site are estimates of the actual costs that might be incurred during a more typical application, due to the following reasons:

- A larger overall treatment area
- An aquifer system with a lower flow and more uniform flow regime
- An aquifer system that is somewhat insulated from the influences of other features (i.e., tides, streams)
- A treatment plot width and spacing pattern that ensures significant hydraulic control.
- A site monitoring and analytical program that is more typical for a commercial application of the technology.

This economic analysis is designed to conform to the specifications for an Order-of-Magnitude estimate. This is a level of precision established by the American Association of Cost Engineers (AACE) for estimates having an expected accuracy within +50 percent and -30 percent. In the AACE definition, these estimates are generated without detailed engineering data. Suggested uses of these estimates are feasibility studies or as aids in the selection of alternative processes. The costs derived for this Phytoremediation application are much more accurate than these specifications, since actual costs incurred from the Carswell NAS Golf Club SITE Demonstration were used. The applicability of these costs to applications of this technology at other sites is limited by the highly specific nature of each application, regional and climatic issues, and the differences in regulatory requirements from state to state. Therefore, labeling these cost figures as "order-of-magnitude" estimates is appropriate.

When considering the cost for a commercial application of a SRWCGT system, one should recognize that public and private landowners establish tree biomass for numerous reasons. Some establish tree biomass as a source of profit from generating fiber, pulp, timber, and fuel. Others establish tree biomass to restore degraded riparian areas in rivers and streams. Still others establish tree biomass to phytoremediate groundwater and soil, which is assumed for the hypothetical model site.

Just as the motives to establish tree biomass differ, the prices associated with tree biomass establishment can also vary markedly from one group to another. To date the

Table 3-1. Estimated Full-Scale Costs for a 200,000 Square Foot Hypothetical Phytoremediation Model Site

Category	Subcosts	% of Total Costs
(1) Site Preparation		
Data Review	$2,500	
Additional Well/Piezometer Installations	$24,000	
Pre-Installation Characterization	$5,000	
Ground Preparation	$3,700	
Tree Planting	$2,500	
Irrigation System Installation	$4,250	
Miscellaneous Site Preparation Tasks	$1,200	
Total Subcost	**$42,650**	**9.1%**
2. Permitting & Regulatory Requirements		
Permits	$5,000	
Reporting	$50,000	
Total Subcost	**$55,000**	**11.8%**
3. Capital Equipment		
Central Main Data Logger (1 unit)	$2,750	
Multiplexers (3 units)	$1,500	
Main Telemetry System (1 unit)	$1,650	
Pressure Transducers (10 units plus cabling)	$18,000	
Soil Moisture Probes (18 units)	$6,000	
Sap Flow Probes (32 units) with Data logger and Telemetry System	$3,593	
Weather Station (1unit) with Solar Panel and Batteries	$3,000	
Groundwater Sampling Equipment (Pumps, Water Quality Meters)	$1,240	
Total Subcost	**$37,833**	**8.1%**
4. Startup and Fixed Costs		
Total Subcost	**$3,783**	**0.8%**
5. Consumables & Supplies		
Irrigation System Materials	$2,000	
Fertilizer and Soil Conditioners	$3,000	
Herbicides & Pesticides	$2,000	
Trees (960)	$480	
Tool Shed	$2,000	
Ancillary Supplies	$10,000 ($1,000/year)	
Total Subcost	**$19,480**	**4.2%**
6. Labor		
Ground Maintenance	$28,000	
Annual Monitoring and Sampling Activities	$80,000	
Total Subcost	**$108,000**	**23.2%**
7. Utilities		
Cellular Service	$12,000	
Water Usage	$900	
Total Subcost	**$12,900**	**2.8%**
8. Effluent Treatment & Disposal		
Total Subcost	**$0**	**0.0%**
9. Residual and Waste Shipping & Handling		
Contaminated Soil Disposal	$7,500	
Total Subcost	**$7,500**	**1.6%**

Table 3-1. Estimated Full-Scale Costs for a 200,000 Square Foot Hypothetical Phytoremediation Model Site (Cont'd).

Category	Subcosts	% of Total Costs
10. Analytical Services		
Pre-Installation Characterization Samples	$38,455	
Annual Monitoring Sampling (10 Years)	$134,400	
Total Subcost	**$172,855**	**37.1%**
11. Maintenance & Modifications		
Irrigation System Repair	$1,000	
Monitoring System Repair or Replacement	$4,000	
Total Subcost	**$5,000**	**1.1%**
12. Demobilization		
Well Abandonment (5 wells)	$1,050	
Total Subcost	**$1,050**	**0.2%**
Estimated Total Cost for Model Site	**$466,051**	

prices charged to establish phytoremediation biomass are significantly more than the prices associated with the establishment of biomass for profit fiber and fuel or riparian restoration biomass. Factors influencing prices for establishing biomass for phytoremediation are: planting techniques employed; depth to groundwater; site specific preparation factors; and, perhaps, the potential customer's lack of familiarity with forestry and agronomic practices and techniques.

Prices can vary markedly on a per tree basis. What one phytoremediation vendor charges for a single tree may be equal to what another vendor charges to establish several hundred trees of the same or similar genus. One also has to remember that this price disparity is for establishing biomass. It doesn't take into consideration additional phytoremediation requirements such as establishing monitoring wells, groundwater chemical analysis, hydrological studies, or the preparation of reports to regulators.

Also, it should be kept in mind that the price asked to perform a given task is often not synonymous with the actual cost to perform that task. The true cost to complete a given task is often closely guarded and not readily shared with anyone. Cost information on a county basis throughout the United Sates is available for anyone wishing to establish short rotation woody crop biomass for profit from the Department of Energy's Oak Ridge National Laboratory Biomass/Biofuels Program (see Appendix A). The costs associated with the establishment of a riparian biomass can be found in a chapter written by Bertin Anderson in a book entitled The Restoration of Rivers and Streams - Theories and Experience edited by James A. Gore (1985).

The phytoremediation system proposed for the model site was designed with the intent to provide not only plume containment but residual contamination source removal. The upgradient portion of the model system would be installed over any pockets of residual contamination. This economic analysis was performed with the understanding that an existing hydraulic control/treatment system (i.e., pump and treat, groundwater interception system, vapor extraction/air sparging) would coexist and remain operative on site until the phreatophytes begin to have a substantial hydraulic affect on the site (i.e., the 3rd or 4th season after planting). By this time the trees would begin to exert a measure of hydraulic control; thereby, reducing the mass flux of contamination in the shallow aquifer beneath the planted zones. Costs associated with any existing remediation systems were not considered in this economic analysis. It is also assumed that these technologies in combination with other measures have addressed the bulk of contamination at the site, leaving only pockets of residual contamination in the vicinity of the former source area. The contaminant source area for the hypothetical model is a former solvent disposal trench. The following basic assumptions regarding the hypothetical model site have been made:

- Groundwater contamination consists chiefly of aqueous phase TCE.
- A drip irrigation system would be required for the first few seasons until the tree roots become established in the shallow aquifer.
- The remediation time-frame would be 10-years.

This economic analysis only presents the costs estimated for the hypothetical model site. A breakdown of actual costs incurred during the 3-year SITE demonstration are not presented in this economic analysis since these costs are of little value to the end-user given the research oriented nature of the study. Many of these costs and cost categories are more inflated than would normally be expected due to a greater amount of people involved, higher labor rates of the engineers and scientists performing the installation, maintenance and monitoring, frequent out of state travel and lodging expenses, and a more extensive analytical and monitoring program. When applicable, some of these costs and experience gained during the SITE demonstration were used to estimate categorical costs for the model site. Some of the assumptions made for the purpose of costing the model site were based upon experience gained during the SITE demonstration. Most of the costs experienced during the SRWCGT demonstration were adjusted down for the model site to make them more representative of the costs associated with a commercial application. Factors that influence the costs associated with a phytoremediation application of a SRWCGT system would include contaminant type and concentration, total treatment area which factors into the number of trees required, dimensions of the groundwater contaminant plume, hydraulic framework of the site, treatment goals, climate, and soil properties, including dominant lithology, fertility, soil moisture, and permeability.

Recent research has suggested the potential of poplar trees to exert a substantial hydraulic effect on shallow groundwater systems, induce reductive dechlorination processes both in the rhizosphere and the tissue of the tree, and withdraw and evapotranspirate groundwater and contaminants directly to the atmosphere. In addition, the use of higher plants for remediation has gained the support of government agencies and the private sector in recent years because of its low cost compared to that of conventional technologies.

3.2 Conclusions

- The cost to demonstrate and validate the phytoremediation of TCE in the shallow groundwater at the Carswell NAS Golf Club over a projected 10 year period is estimated to be $1,600,000. Costs were based upon two treatment plots oriented perpendicular to the direction of groundwater flow and measuring 12,500 ft^2 each, each plot consisting of two different types of Eastern Cottonwoods (Populus Deltoides), a tighter than normal spacing to accelerate hydraulic capture of the shallow aquifer in consideration of the abbreviated evaluation period, and a total of 660 trees. The costs were also based upon information collected over the 3-year remediation period. It should be noted that the majority of costs with the Carswell NAS Golf Club Phytoremediation Demonstration were for extensive technical support, reports, analytical program, posters, papers, and presentations to validate various changes in the geochemistry, tree water usage, and groundwater hydrology. Costs at an actual phytoremediation site would be lower. Under ideal site conditions the economics of short rotation woody crops coupled with the costs of long term monitoring similar to that conducted for natural attenuation will result in costs well below those at the Carswell NAS Golf Club.
- If a site is conducive to short rotation woody crop forestry techniques, serious consideration should be given to the methods and techniques developed over a period of thirty years by the Department of Energy's Oak Ridge National Laboratory Biomass/Biofuel Program. When large acreage of tree biomass is required to accomplish a given phytoremediation objective, a cooperative forestry agreement with a local wood burning power plant or pulp mill should be explored as a means to offset the majority of the cost of establishing the biomass. Cooperative forestry ventures enable landowners to let another party grow a short rotation woody crop of trees on their property in exchange for a portion of the revenue (typically 40-45%) generated by the sale of the biomass.
- The total cost to remediate residual contamination at the hypothetical model site and attain hydraulic influence was estimated to be $466,051. The model site also consisted of two plots orientated perpendicular to the shallow aquifer flow direction and measured 48,000 ft^2 each, a tree spacing pattern of 10 feet, a total of 960 trees and a 10 year remediation period. As one increases the acreage of biomass established, the cost per acre to phytoremediate shallow groundwater should also decrease accordingly. The long term technical support and reporting costs of most phytoremediation projects will exceed the costs to establish the necessary biomass. Small sites will have essentially the same technical support and reporting requirements as larger sites. The documentation of biomass influences on groundwater chemistry and hydrology and the preparation of reports to regulators will be the largest cost component of a SRWCGT system. Once the trees mature and reach their operational potential (hydraulic influences and enhanced biodegradation), the remedial project manager can petition regulators for less stringent long term monitoring.
- For the hypothetical model site analytical (37.1%) followed by Labor (23.2%) were the most predominant cost categories.

3.3 Factors Affecting Estimated Costs

The design, installation, monitoring and maintenance requirements for a tree based phytoremediation system is highly site specific. As a result, a number of factors could affect overall cost. These factors might include, but are not limited to:

- Total Treatment Area
- Distribution and Magnitude of Contamination
- Climate
- Hydraulic Framework of the Site
- Physical and Chemical Properties of the Soil
- Treatment Goals

The total size of the treatment area would logically factor into the number of trees needed, the amount of time required to install the system (ground preparation activities, installing an irrigation system, planting the trees, installing system monitoring stations), the amount of nutrients, soil conditioners, mulch, pest and disease control substances, the volume of water consumed for irrigation purposes, as well as the man-hours needed to perform periodic maintenance tasks.

The distribution of contamination would determine the placement, alignment and dimensions of the tree plantations. If the objectives of the project are mainly to reduce the mass flux of groundwater contamination transported across the planted areas through hydraulic control, then it would only be necessary to place the plantations in a position enabling them to intercept contaminants released from the most downgradient source. The type of contaminant and magnitude of contamination (assuming it is a halogenated species as was the case at the Carswell NAS Golf Club) would factor into the type of tree chosen and the overall time needed to remediate the site. Some species of trees are known to be more tolerant to higher concentrations or to specific chemicals. Availability of these trees may factor into cost.

Climatic factors, such as the start and length of the growing season, annual precipitation and the amount of solar radiation would control the amount of time during the year that the trees exert a hydraulic control on the aquifer, biologically enhance subsurface conditions, and remove contaminants via evapotranspiration. Climatic factors would also determine the need for an irrigation system during drought conditions (i.e., augment the aquifer and prevent the trees from dying). Shorter growing seasons could lengthen the time needed to reach remediation goals.

The hydraulic framework of the site (i.e., aquifer size and yield, groundwater velocity and flow direction, depth to groundwater, aquifer thickness, homogeneity and grain size of aquifer materials) should be used as a guide when deciding upon tree density, plot size, and number of plots needed. Hydraulic conditions at the site would also control the time needed for the trees to reach full hydraulic and transpirational potential either shortening or lengthening the time the system starts to have a significant hydraulic impact on the site. Although research has shown that hydraulic control is the principle mechanism responsible for reductions in the mass flux of contamination transported across the planted area during the early stages of tree-based treatment, other mechanisms, especially microbially mediated reductive dechlorination may become just as prominent after the third or forth season. In fact, reductive dechlorination might be the most important mechanism operating during the dormant season.

The physical and chemical properties of the soil would include soil moisture retention, soil moisture profiles, drainage, infiltration rates which would determine the need and design of an irrigation system to help jump start the trees. These soil properties will also determine the need for providing some type of groundcover that would force the trees to seek out the aquifer as a source of water rather than becoming dependent on rainwater infiltrate. Other soil properties that have the potential for impacting cost would be nutrient availability and the organic content of the soil. This would determine the amounts of fertilizer and soil conditioners needed over the course of the project and also effect the maintenance schedule, possibly increasing the amount of man-hours needed.

Remediation goals would be site specific. Certain goals may be based upon specific soil and/or groundwater cleanup criteria or based upon a site specific receptor risk. Remedial goals at a site may fall into two categories: source removal or source control. Whatever the remedial goals might be, certain design features and the time needed to effect the necessary changes would ultimately affect total cost.

3.4 Issues and Assumptions

This section summarizes the major issues and assumptions used for calculating costs for using a similar phytoremediation system at a hypothetical model site. In general, assumptions are based on information provided by the developer and observations made during this and other SITE demonstrations projects.

3.4.1 Site Size and Characteristics

This economic analysis assumes that an area wide site characterization had already been performed as part of a remedial investigation or its equivalent, and that only a series of limited but highly specific hydrogeological, geochemical and waste characterizations would be performed as necessary to assist with design parameter decisions, establish appropriate site preparations methods, and determine maintenance tasks and schedule.

For the purpose of conducting this economic analysis, the conceptualized model site for a commercial application of the tree-based phytoremediation system will have a total treatment area of 200,000 ft^2 or roughly 4.6 acres. Surface topography would generally be flat. Current vegetation would consist of several mature deciduous trees. Ground cover would consist mostly of grass with a few bare patches. The model site would be accessible via paved roads. Electrical and telephone services and a metered potable water source would also be available. The source of contamination at the site has been linked to a former trench that the facility once used to dispose of various waste solvents. The trench formerly occupied an area of 7,500 ft^2 on the north end of the property. TCE is the principal contaminant of concern at the model site. The bulk of solvent-based contamination at the site has already been addressed by another remediation system (e.g., pump and treat, steam enhanced vacuum extraction). Residual amounts of contamination still occur in pockets in the vicinity of the former trench. These pockets of contamination continue to be a source of groundwater contamination at the site. Concentrations on the order of several thousand micrograms per liter still occur in the groundwater in the vicinity of the former trench. The concentrations decrease by an order of magnitude 500 feet downgradient of the source area.

The surface soil across the site is assumed to be a very compact 12 to 18 inch layer of silty clay to clayey silt. Infiltration is generally poor accept along a network of widely spaced desiccation cracks that occur throughout the site. Depth to groundwater is generally 10 to 15 feet BLS across the site. Aquifer materials are being assumed to consist predominantly of silty fine sands with a few hydraulically isolated lenses of coarser material. A hypothetical conductivity (k) value of 10^{-2} cm/s is being assumed for this exercise along with a porosity value of 35 percent. Shallow aquifer thickness is being set at 5 feet producing an estimated aquifer water volume of 2,618,000 gallons. The maximum hydraulic gradient across the site is 2.20 percent with a principal groundwater flow direction to the south. Groundwater velocities for the model site have been estimated at 0.62 feet/day or 226 feet/year. Groundwater flow across a cross-sectional slice in the upgradient portion of the site has been estimated to be around 9,300 gpd.

3.4.2 System Design and Performance Factors

The goal of the tree-based phytoremediation approach designed for the model site is two fold: remove residual contamination in the subsurface near the former trench, and reduce the mass flux of solvent based contamination in the upper aquifer through a combination of hydraulic control and in-situ microbially mediated reductive dechlorination. Based upon the type and levels of contamination persisting at the site, it is assumed that hybrid poplar trees would be used at the site. The species selected would be native to the area, possess a tolerance to the levels of chlorinated ethenes found at the site, have a fairly long life-span, have some drought tolerance, and have a natural resistance to pests and disease. As with the Carswell NAS Golf Club site, poplars also have the advantage of fast growth, high transpiration rates, and phreatophytic properties. A sufficient number of these trees would need to be planted in a series of plots to address a calculated volumetric flux of 9,300 gpd entering the upgradient portion of the treatment area. The design should also have enough reserve capacity built into it so as to be capable of handling twice the calculated volumetric flux. Based upon a conservative per tree uptake rate of 20 gallons per tree per day (gptpd) (uptake rates as high as 40 gptpd have been reported for mature hybrid poplars on very hot days), a minimum of 466 trees will be needed to handle the calculated flux of groundwater entering the system.

The model site will have 960 trees divided evenly between two 120 by 400 foot plots positioned perpendicular to the direction of groundwater flow and separated by a 100 foot buffer zone. Figure 3-1 depicts the layout of the model site used in the economic analysis. Each plot will consist of 12 rows of trees planted 10 feet a apart. Each row will have 40 trees. The upgradient plot will be positioned over the former trench area so as to biologically enhance the subsurface environment in a manner that promotes the reductive dechlorination of residual chlorinated ethenes.

3.4.3 System Operating Requirements

The benefit of using a system like phytoremediation is that it only requires minimal attention once the trees are planted, resulting in an O&M cost savings. The technology has been described as a solar powered pumping and filtering system that operates on its own. Phytoremediation systems also requires minimal capital investment. Capital expenditures tend to be limited to monitoring instruments. The purchase cost for some monitoring equipment (e.g., Sap Flow Monitoring System, pumps and water quality meters) can be spread out over as many as 10 other projects. Other equipment (e.g., data loggers, multiplexors, weather station) will be dedicated to just one project and likely become obsolete at the end of the treatment period. Periodic maintenance is required to clear and replant dead trees, remove broken branches, prune healthy trees, apply pest and disease control substances as needed, add fertilizer and make repairs to the irrigation system and monitoring system.

The hydraulic influences of the system are limited to the growing season which can vary depending upon geography. In most climates the growing season refers to the period between April and September. The period between October and March represents the dormant period when the trees temporarily stop pumping groundwater. Individual trees can begin affecting the shallow aquifer systems as early as 1 year after planting. Special planting procedures and root training methods using drip irrigation can be used to encourage young trees to seek out water

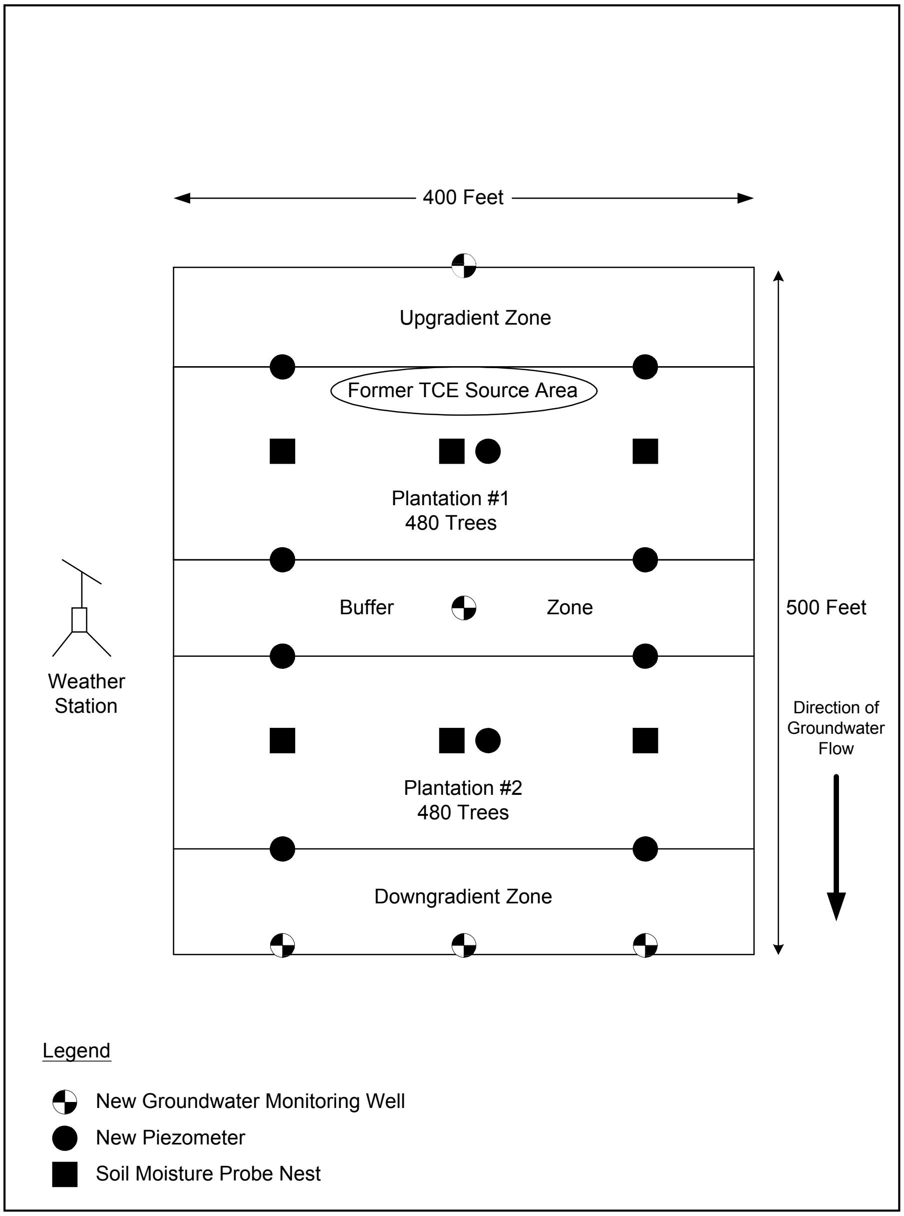


Figure 3-1. Layout of 200,000 square foot hypothetical model site for cost analysis.

from the aquifer rather than infiltration from rainfall; however, tree roots will reach the water table without special planting procedures or root training methods. In most cases it takes 3 to 4 growing seasons before individual trees reach their full transpirational potential. It may take up to an additional 10 years, after this milestone for the system to achieve final remediation goals established for the site. Removal of chlorinated ethenes from the subsurface may be accomplished through several mechanisms including enhanced bioremediation in the rhizosphere due to the release of various plant exudates through the root system resulting in a process called reductive dechlorination, or direct uptake of the contaminants through the root system and release to the atmosphere via evapotranspiration.

3.4.4 Financial Assumptions

All costs are presented in 2001 U.S. dollars without accounting for interest rates, inflation or the time value of money. Insurance and taxes are assumed to be fixed costs lumped into "Startup and Fixed Costs" (see Section 3.5.4). Any licensing fees paid to a developer, for using proprietary materials and implementing technology-specific functions, would be considered profit. Therefore, these fees are not included in the cost estimate.

3.5 Results of the Economic Analysis

Using the general assumptions already discussed, the results of the economic analysis of the SRWCGT process are presented in Table 3-1. These assumptions are discussed in more detail by cost category below. Unless otherwise specified, information presented in the following sections focuses on issues and costs related to the model site.

3.5.1 Site Preparation

Costs associated with Site Preparation have been divided up into six (6) subtasks: Data Review, Additional Monitoring Well/Piezometer Installations, Pre-installation Characterization Studies, Ground Preparation, Tree Planting, Irrigation System Installation, and Miscellaneous Site Preparation Tasks.

Data Review - Successful application of a tree-based phytoremediation system requires careful planning to ensure that the contamination will be adequately remediated and hydraulic control can be achieved. Planning would begin with a thorough review of existing data sources which would include any number of reports generated for the site as the result of other environmental investigations (i.e., Remedial Investigation/Feasibility Study (RI/FS) Reports, Record of Decisions (RODs), Preliminary Assessments (PA), Corrective Action Reports, Remedial Design Reports, Environmental Impact Statements). For the purpose of this economic analysis, it is assumed that the model site has already been extensively investigated. The purpose of the data review is to identify potential data gaps as they pertain to the design and operation of the phytoremediation system. The estimated cost for data review is $2,500. This cost was based upon a project scientist billing out at $50/hr spending about 50 hours researching existing literature and identifying data gaps.

Additional Monitoring Well/Piezometer Installations - For the model site it is assumed that the existing well network is inadequate for providing all the monitoring needs for the project. It is assumed that the model site already has 15 existing wells. An additional 5 monitoring wells and 10 piezometers will require installation to more adequately define hydraulic gradient, variations in aquifer thickness, zones of higher permeability, depth to groundwater and hydraulic conductivity. Although some sites may require fewer wells/piezometers, it would be a rare case indeed to have a site that required no additional wells/piezometers. The cost for drilling, installing and developing these additional monitoring wells/piezometers at the model site is estimated at $24,000. The subcontract cost per 6-inch diameter well and piezometer is estimated at $2,800 and $800 respectively. It is assumed that monitoring wells would require the use a truck-mounted drill rig for drilling and installation. The less expensive GeoProbe® System could be used to install the piezometers. The total subcontract cost associated with this subtask is estimated at $22,000. Labor associated with subcontract oversight and the collection of 30 soil samples during drilling is estimated at $2,000. This estimate is based upon a mid-level geologist billing out at $50/hr working a total of 40 hours (5 days @ 8 hours/day).

Pre-installation Characterization Studies - A number of pre-installation characterization studies may need to be conducted to address data gaps identified during the data review subtask. Data gained from these studies would contribute to decisions concerning the type of tree that should be used, planting density, the total number of trees needed to achieve hydraulic control, the number, position and dimensions of the tree plots, the need for specialized planting procedures, the need for a drip irrigation system, and the types and amounts of fertilizer and soil conditioners. The types of studies conducted are highly site specific and might include:

- Aquifer testing of existing and new wells to better define the hydraulic properties (i.e, hydraulic conductivity, aquifer transmissivity, hydraulic yield, hydraulic connectivity) of the contaminated aquifer beneath the treatment plots
- Groundwater and soil sampling to better define certain geochemical and physical properties, such as dissolved oxygen, redox potential, macro and micro nutrients, pH, conductivity, particle size distribution, soil moisture, plus evidence of intrinsic biological activity and reductive dechlorination in the rhizosphere of native trees. Sampling will also better define the extend and magnitude of contamination in the areas of the proposed tree plots.
- Evapotranspirational studies (Sap Flow Measurements and root biomass studies) can be conducted on several species of existing trees in the study area to evaluate current removal of water from the aquifer (saturated zone) and provide a means of estimating upper-bound levels of transpiration that may be attainable by the proposed tree-based phytoremediation system at the model site.
- Tissue samples (i.e., leaves, stems and roots) can be collected from several species of existing trees in the study area to analyze contaminant uptake in plant organ systems and the potential for metabolic transformations.

The estimated cost for the proposed pre-installation characterization study at the model site is $5,000. This value represents labor costs associated with the purging of monitoring well prior to sampling, the collection of water level measurements, the collection of groundwater samples from existing and new wells, the collection of tree tissue samples from existing trees and the recording of various field measurements needed to fill some of the data gaps. Groundwater sampling associated with this pre-installation characterization would be limited to just the new monitoring wells/piezometers and 10 existing monitoring wells for a total of 25 wells sampled. It is assumed that some of the existing wells will be of little value to this present study as a consequence of either their location or design. Water level measurements would be obtained from all site wells (45 total). Tree tissue samples will be obtained from 12 to 13 existing trees resulting in a total of 25 tissue samples collected. The $5,000 estimate is based upon two junior level scientists billing out at $50/hour working 10 hours per day over a 5 day period. It is assumed that the pre-installation characterization subtask as with the drilling oversight work would be staffed from a local office; therefore, no travel/lodging costs have been included. The off-site analytical costs associated with this subtask are presented in Section 3.5.10, Analytical Services.

Ground Preparation - It is assumed that ploughing and discing will be necessary in the areas designated for tree planting to facilitate fertilizer infiltration, increase soil porosity, ease planting and foster vigorous root growth. The appropriate types and amounts of nutrients and conditioners (i.e., organic matter, drainage-enhancing media, etc.) will be mixed into the soil at this time. Selection and application rate of these materials would be based upon the results of geochemical and physical analyses conducted on model site soils during the additional site characterization studies. The plots will also be ripped and/or trenched to facilitate the planting of the trees and setting the piping for the irrigation system. Costs associated with this subtask are comprised of labor and equipment rental fees. Based upon the size of each plantation, and experience gained at the Carswell NAS Golf Club demonstration, it is estimated that ground preparation activities would take around 5 days. Labor associated with ground preparation activities has been estimated at $1,250. This figure was based upon using a technician billing out at $25/hour and a work day estimate of 10 hours. Discing, ploughing, ripping and trenching will be accomplished using equipment rented locally. Ploughing and discing will likely be accomplished with at tractor. The tractor and the plough will likely be needed for 5 days at a rate of $1,500 per week. The disc attachment will probably rent out at $200 dollars a day and will only be needed one day. The walk behind trencher will probably be rented for a week at $750/week. It will likely be needed again for installing the irrigation lines. Total rental costs for ground preparation activities at the model site are estimated at $2,450. Total cost for ground preparation work at the model site has been estimated at $3,700 or approximately $804/acre. This estimate does not reflect costs associated with certain consumable items that would be used during this stage (i.e., fertilizers, amendments). These consumables are presented in Section 3.5.5., Consumables and Supplies.

Tree Planting - Data obtained from the pre-installation characterization study would aid decisions regarding the number, size, geometry and orientation of the tree plots as well as tree planting density. For the model site, it is assumed that 960 trees divided evenly between two 120 by 400 foot plots would be needed. Trees will be placed in rips or trenches created to the desired depth. These trenches would then be backfilled with a rooting mixture of fertilizer, organic-rich soil, and other amendments. The cost to plant the trees at the model site has been estimated at $2,500. This cost only reflects the labor associated with planting the trees. Is assumed that two technicians billing out at $25/hour working 10 hours per day for a total of 5 days would be sufficient to complete the job. The costs related to the purchase of the 960 trees for the model site are presented in Section 3.5.5., Consumables and Supplies.

Irrigation System Installation - A drip irrigation system has been costed into the model site to jump start the trees. This subtask involves the installation of irrigation system components (i.e., PVC mainlines and sub-mains, drip tubing arrays, emitters, valving, backflow preventors, pressure regulators, filters, end caps), any trenching, staking and testing of the system. Costs associated with the installation of an irrigation system at the model site are comprised of labor and equipment rental costs. Components of the irrigation system are priced separately in Section 3.5.5., Consumables and Supplies. Based upon the layout and size or the tree plots at the model site and experience gained at the Carswell NAS Golf Club demonstration, it is assumed that installation activities will take 7 days. Labor costs associated with the installation of the irrigation system at the model site are estimated at $3,500. This cost is based upon two technicians with a $25/hour labor rate working 10 hour days throughout the 7 day installation period. The costs associated with rental of the trencher are based upon a weekly rate of $750. Total costs for the irrigation system installation at the model site are estimated at $4,250.

Miscellaneous Site Preparation Tasks - Miscellaneous tasks would include connecting to the facility's water supply ($1,000) and installing a small lockable tool shed to keep equipment and supplies in when no other arrangements can be made with the site owner ($200). The purchase cost of the shed is listed in Section 3.5.5., Consumables and Supplies. Connecting to a facility's electrical power main is estimated to cost in the range of $2000, but for this analysis it is assumed solar panels and rechargeable batteries will be used to power all monitoring equipment (At the Carswell NAS Golf Club Site electrical power was supplied thru solar panels and 12 volt car batteries). Other possible voluntary expenses, not included in this analysis, are renting an office trailer equipped with a phone and fax, and rental of a portable toilet. The office/supply trailer estimate was based upon a $500/month rental over a 10 year remediation period. Electricity would be needed to provide lighting, air conditioning and heat to the office/storage trailer so this could be a significant expense in places, like Texas, with long hot summers. The expense of an air-conditioned office trailer was considered at the

Carswell NAS Golf Club Site and dismissed. Summer fieldwork is inherently hot. United States Air Force, United States Geological Survey, United Sates Forest Service, and other support personnel working at the Carswell NAS Golf Club during the summers months and record recent droughts successfully employed simple light loose fitting clothing, hats, cold drinks, and tarps to minimize heat stress.

For this analysis, generic site preparation responsibilities such as site clearing, demolition, grading, road building, surveying, utility clearance, staging area construction, site fencing, auxiliary facility construction (i.e., storage area building, decontamination facility) and main utility connections were all assumed to have been performed by the property owner/manager. None of these costs have been included here.

3.5.2 Permitting and Regulatory Requirements

Depending upon the classification of the site, certain RCRA requirements may have to be satisfied. If the site is an active Superfund site it is possible that the technology could be implemented under the umbrella of existing permits and plans held by the Potentially Responsible Party (PRP) or site owner. Otherwise, few permits will likely be required to operate a tree-based phytoremediation system such as the one proposed for the model site. No permit costs were experienced for the Carswell NAS Golf Club demonstration system. Certain regions or states have more rigorous environmental policies, and a number of permits might be required. In addition, permit requirement and associated permitting costs can change rapidly. Certain municipalities might require permits to construct or operate the phytoremediation system. It's possilbe that these requirements might be waived considering the nature of this technology. Permits might also be required for the installation and abandonment of monitoring wells. Permit costs for the model site are being estimated at $5,000.

State and Federal regulatory authorities might require the preparation and submittal of a series of reports including but not limited to a Corrective Action Report, Conceptual Design Reports or even Environmental Impact Statements. The cost associated with preparing these reports has been estimated at $50,000.

3.5.3 Capital Equipment

Capital equipment costs associated with implementation a tree-based phytoremediation system would be comprised entirely of field instrumentation needed to monitor the system. Most of the capital equipment cost estimates presented in this economic analysis are based upon present day costs for various monitoring components and knowledge gained from the Carswell SITE demonstration. It has been assumed that many of the components of the field monitoring system will be a one time purchase and will have no salvage value at the end of the project. Given the length of the proposed treatment period (10 years) much of the equipment will either be obsolete (due to advances in computer technologies) or be near the end of its operational usefulness (based on an estimating 10 year life-span). Many of the monitoring components will be dedicated to this project alone (i.e., soil moisture sensors, weather station, some data loggers, multiplexors, pressure transducers) and involve permanent installations (i.e, weather station). The cost of some other components could potentially be spread out over 7 other projects (i.e., Sap-Flow Probes, Sap-Flow Data Logger and Telemetry System, groundwater sampling pumps, water quality meters, electronic water level indicator).

As with any project, monitoring equipment can vary in sophistication and cost. The amount invested in equipment is ultimately a function of the quantity and quality of data needed to support specific objectives. For purposes of this analysis, most of the monitoring equipment, with the exception of the sap flow sensors, will be connected to one central data logger (approximately $2,750 with software) through three multiplexers (approximately $500 each). The central data logger will be connected to a telemetry system. The telemetry system will allow the user the capability of remotely accessing the data, performing system checks, and reprogramming the data logger if necessary (approximately $1,650).

For a tree-based phytoremediation system, such as the one proposed for the model site, equipment would be needed to monitor changes in water level across the site as a means of assessing tree root mass development and transpirational potential of the maturing trees. Continuous water level data can be obtained through a series of pressure transducers placed in a number of wells, in this case 15 wells and 10 piezometers. It is assumed that 10 pressure transducers would be used for the model site. These transducers would be connected to a central data logger which would be programmed to collect and record water level measurements at set times over the course of treatment. Water levels in the other wells would be obtained manually at regular interval using an electronic water-level indicator. Costs estimated for the pressure transducers, cable, and other related equipment would be $18,100 (each pressure transducer is approximately $810 plus approximately $2.00 per foot of cable). A lesson learned at the Carswell NAS Golf Club was that float water levels should be avoided because tree roots in well casing tend to hang water floats up and give erroneous water level readings. Another reason to avoid water floats is that they are often made of carbon steel, which can interfere with geochemical measurements.

Soil moisture probes would also be used to monitor changes in soils moisture at various depths. These instruments will likely be stacked at six locations to provide an accurate profile of soil moisture content from surface to the top of the water table. Three locations will be selected in each plot for soil moisture measurements. Three soil moisture probes will be installed at each location in a shallow, medium and deep configuration. A total of 18 soil moisture probes will be used for the model site. The soil moisture probes, as with the pressure transducers, will be connected to the same central data logger, which can be remotely accessed and programmed. Total estimated costs associated with the soil probe system would be $6,000 (each probe is approximately $190 plus approximately $0.70 per foot of cable).

A Sap Flow/Sap Velocity/Plant Transpiration system will be used for measuring the transpiration rates and water usage of the trees through each growing season. The system enables the simultaneous monitoring of up to 32-sap flow sensors. The sap flow equipment cost (data logger, probes, gauges, multiplexers, cables, telemetry equipment, and software) is estimated at $25,150. The cost for this item can be spread out over 7 other projects. The adjusted cost for this item at the model site is $3,593. Due to advances made by the United States Forest Service's Coweeta Hydrologic Lab at the Carswell NAS Golf Club Site, Orlando, Florida, and Denver, Colorado and current on-going efforts to improve the physiologically based tree PROSPER Transpiration Model, routine employment of sap flow device at phytoremediation sites will most likely become unnecessary.

An on-site weather station will be used to aid with interpretations of transpiration rates. The weather station will be capable of measuring temperature, pressure, relative humidity, wind direction, wind velocity, rainfall, soil temperature, solar radiation. A complete on-site weather station would cost approximately $3,000 (including a solar panel and rechargeable batteries), assuming it is connected to the central data logger and telemetry system mentioned earlier.

Periodic groundwater sampling will require the use of a groundwater sampling pump and a water quality meter capable of providing continuous measurements of temperature, conductivity, dissolved oxygen, oxygen reduction potential and pH. Groundwater sampling will also require the use of an electronic water-level indicator. It is assumed that groundwater sampling will employ micro-purge techniques. As was the case with the Sap-Flow equipment, the cost of the groundwater sampling equipment can be spread over 7 other projects. It is assumed that a simple peristaltic pump, capable or running off a car battery and costing around $1,200, will be used throughout the treatment period. The water quality meter, which will have data logging capability, will cost approximately $7,000. An electronic water level indicator will cost $479. The adjusted cost for groundwater sampling equipment planned for the model site is $1,240.

3.5.4 Startup and Fixed Costs

From past experience, the fixed costs for this economic analysis are assumed to include only insurance and taxes. They are estimated as 10 percent of the total capital equipment costs, or $3,783.

3.5.5 Consumables and Supplies

Consumable and supply items for the model site application would include plumbing supplies for the drip irrigation system (i.e., PVC mainlines and sub-mains, drip tubing arrays, emitters, valving, backflow preventors, pressure regulators, filters, end caps), fertilizer and soil conditioning materials, mulch, pest and disease control materials, the trees, ancillary supplies for monitoring equipment (i.e., tubing for peristaltic pump, tool shed), miscellaneous expendable landscaping supplies (i.e., rakes, shovels, pruners, garden sprayers, etc.) and health and safety supplies. Piping and fittings for the irrigation system are estimated to cost $2,000 (with a 20% salvage value). Fertilizer and soil conditioner consumption is based upon a total tree plot area of 96,000 ft^2 and 10 years of treatment. The estimated cost for fertilizer and soil conditioners is $3,000. The same assumptions used for estimating the cost of fertilizer were used for estimating the cost of pest and disease control materials. Pest and disease control materials are estimated to cost $2,000 over the term of treatment at the model site. As previously discussed, it is estimated that 960 trees will be needed at the model site. Based upon an estimated purchase price of $0.50 per tree (assuming volume discounts apply), total tree cost has been estimated around $480. Tree cost will vary based upon geography and tree species. The tool shed, previously discussed in Section 3.5.1, will cost around $2,000. Ancillary supplies for monitoring equipment tubing, gardening supplies and health and safety supplies are estimated at $1,000/year totaling $10,000 over the term of project.

3.5.6 Labor

Hourly labor rates include base salary, benefits, overhead, and general and administrative (G&A) expenses. Travel, per diem, and rental car costs have not been included in these figures. Local travel to the site is assumed for the model site. If a site is located such that extensive travel will be required, travel related cost would significantly impact labor costs. Labor costs associated with a tree-based phytoremediation system such as the one proposed for the model site would be limited to general ground maintenance tasks and monitoring and sampling events.

Ground maintenance tasks at the model site would consist of the periodic removal of dead branches, pruning, replanting and clearing dead trees, weeding, grass mowing and application of pest and disease control substances as well as fertilizers. Labor associated with ground maintenance would likely be conducted monthly and occur primarily during the growing season. It is assumed that ground maintenance tasks would require a landscaper working an 8-hour day for 1 day each month. In most regions, ground maintenance will be required 7 months out of the year. Assuming a landscaper labor rate of $50/hour, ground maintenance labor for the term of treatment (10 years) is estimated at $28,000. The amount of ground maintenance ultimately required will be a function of the actual visibility of the site. Sites with higher visibility require more attention then remote sites. After the canopy of the trees has closed, often the growth under the trees rarely needs cutting. Another option to reduce long term landscaping costs is to employ some form of shade tolerant ground cover that requires little or no maintenance.

Labor associated with monitoring and sampling will be reduced somewhat by the various data logging capabilities of the instrumentation installed at the model site. This instrumentation will enable real-time remote access and monitoring of information pertaining to tree growth, hydraulic conditions and soil moisture. Monitoring and sampling events will likely involve physical tree measurements (i.e., tree height, canopy width and tree trunk diameter), additional water level measurements, calibration checks on automated monitoring systems, groundwater sampling and tree sap-flow measurements. It is assumed that 1-2 monitoring and sampling events would be scheduled each year during the growing season. Each event would require 2 people, working a standard 8-hour work day, 5 days to complete. It is assumed that the tasks associated with monitoring and sampling would be accomplished by two junior level scientists billing out at $50/hour. Total labor costs associated with monitoring and sampling are estimated at $4000 per sampling event, or approximately $80,000 over a ten-year period assuming two sampling events per year. Labor associated with groundwater, soil and tissue sampling during Site Preparation is presented in Section 3.5.1.

To reduce costs a project manager may want to consider reducing the number of sampling events in the early years as the trees establish themselves. Once anaerobic groundwater conditions and maximum hydraulic influences are established, the remedial project manager might consider petitioning the appropriate regulators for a less stringent monitoring program to reduce costs.

The labor associated with the other tasks, such as site preparation, maintenance and modification, and demobilization have been assigned to other categories. Analytical costs associated with monitoring/sampling events are presented in Section 3.5.10., Analytical Services.

3.5.7 Utilities

A major utility cost for the project will be cellular phone service for each telemetry system at the site. The model assumes two telemetry systems with a monthly cellular service fee of approximately $100 or approximately $12,000 over a ten-year period.

Another utility required for this project would be water used by the drip irrigation system. The drip irrigation system would only be required until the roots reach the groundwater. It is assumed that the irrigation system would only be required for 2 years, but would be available to augment the aquifer in situations of severe drought. Cost associated with water consumption for the model site are estimated at $900

No costs for electrical usage is included, since solar panels and rechargeable batteries will be used to power the monitoring systems.

3.5.8 Effluent Treatment and Disposal

No costs were assigned to this category because the transpirate from the trees is not regulated.

3.5.9 Residuals & Waste Shipping, Handling, and Storage

It is assumed that as many as 15 drums will be needed to dispose of waste soil, drill cuttings and contaminated water generated by purging and drilling. Based upon the classification and disposal requirements for the types of contaminants found in the subsurface at the model site, the cost to manifest, transport, and dispose of these drums was estimated at $500/drum. The total cost to dispose of these drums is estimated to be $7,500. Additional drums might be generated for the disposal of contaminated PPE items. It is assumed that no more than 2 PPE drums of PPE contaminated enough to require special waste handling and disposal would be generated over the course of treatment. Disposal of these drums would be nominal and therefore have not been included here.

3.5.10 Analytical Services

It was assumed that off-site analytical support would be needed during any sampling associated with the pre-installation characterization study and during each monitoring and sampling event conducted at the model site. As discussed previously, the purpose of samples collected during the pre-installation characterization stage is to support decisions on tree type, plot placement and dimensions, number of trees, planting density, fertilizer schedule, the types and amounts of soil conditioners needed, and irrigation system design. Twenty-five (25) groundwater samples would be analyzed for volatile organic compounds (VOCs), ICP metals, total organic carbon (TOC), common ions, and pH. Thirty (30) soil samples would be analyzed for VOCs, ICP metals, TOC, pH, percent moisture, porosity, particle size distribution, nitrate-nitrites, and phosphates. Twenty-five (25) tree tissue samples would be analyzed for VOCs. Pre-installation characterization analytical costs for the model site are estimated to be $38,455.

Samples collected for off-site analyses during each monitoring and sampling event would consist of 15 groundwater samples per event. These samples would be collected to monitor changes in VOC contaminant concentrations and the spatial distribution of VOC contaminants in the groundwater. Analytical costs associated with monitoring and sampling events are estimated at $13,440 per year, assuming two sampling events per year. Total analytical costs for monitoring and sampling events conducted over the 10 year treatment period are estimated at $134,400. Additional analytical costs might be incurred if the regulators require soil verification samples to be collected.

3.5.11 Maintenance and Modification

It is assumed that repairs will have to be made periodically to the drip irrigation system. The irrigation system may have to be drained during the winter months to prevent ice damage. Estimated repair costs for the model site's irrigation system are assumed to be around $1,000. It is also possible that the weather station, soil moisture probes, and data logger may get damaged over the course of treatment due to grounds keeping activities, lightning strikes, etc., therefore, it is assumed that $4,000 would be needed for replacement parts (see Section 3.5.6 Labor for associated costs).

3.5.12 Demobilization

Demobilization of a plant-based phytoremediation system would basically involve the proper abandonment of all wells. Trees can most likely be left in place unless and arrangement has been made to harvest and sell the wood. Well abandonment requirements vary from state to state, as a result abandonment costs can vary as well. Use of a drill rig to abandon the 5 additional wells at the model site would be approximately $250, and the charge for well abandonment would be approximately $8 per foot. This price includes labor, materials, insurance, and taxes. The five additional wells at the model site represent 100 linear feet that will require abandonment. The total cost for demobilization is estimated at $1,050.

SECTION 4
TREATMENT EFFECTIVENESS

This section describes the effectiveness of the phytoremediation system in controlling the migration of a trichloroethene (TCE)-groundwater plume during a field-scale demonstration of the technology at a site in Fort Worth, Texas. Information provided in this section includes: (1) site conditions prior to treatment, (2) implementation, and monitoring, (3) objectives, including the methodologies implemented to achieve these objectives, and (4) results and performance, including system reliability and process residuals.

4.1 Background

This field-scale demonstration was a cooperative effort between the U.S. Air Force Aeronautical Systems Center Acquisition, Environmental, Safety and Health Division (ASC/ENV), the U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP), the U.S. Environmental Protection Agency (USEPA) Superfund Innovative Technology Evaluation (SITE) Program, and the U.S. Geological Survey (USGS). The overall purpose of this effort was to demonstrate the feasibility of purposefully planting eastern cottonwood trees to help remediate shallow TCE-contaminated groundwater in a subhumid climate. Specifically, the study was undertaken to determine the potential for a planted system to hydraulically control the migration of contaminated groundwater, as well as biologically enhance the subsurface environment to optimize in-situ reductive dechlorination of the chlorinated ethenes present (trichloroethene and cis-1,2-dichloroethene). To assess the performance of the system, hydrologic and geochemical data were collected over a three-year period. In addition to investigating changes in groundwater hydrology and chemistry, the trees were studied to determine important physiological processes such as water usage rates, translocation and volatilization of these volatile organic compounds, and biological transformations of chlorinated ethenes within the plant organs. Since planted systems may require many years to reach their full remediation potential, the study also made use of predictive models to extrapolate current transpirational hydrologic conditions to future years. In addition, a section of the aquifer that underlies a mature cottonwood tree (~20 years old) was investigated to provide evidence of transpiration rates and geochemical conditions that may be achieved at the site when the planted trees reach full maturity.

The selected site is on the north side of the Carswell Golf Course (CGC) at the Naval Air Station Fort Worth (NAS Fort Worth) about one mile from the southern area of the main assembly building at Air Force Plant 4 (Plant 4). The assembly building is the primary suspected source of TCE at the demonstration site. Historically, the manufacturing processes at Plant 4 have generated an estimated 5,500 to 6,000 tons of waste per year, including waste solvents, oils, fuels, paint residues, and miscellaneous spent chemicals. Plant 4 is on the National Priorities List and is being remediated in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA). TCE is believed to have leaked from degreasing tanks in the assembly building at Plant 4 and entered the underlying alluvial aquifer. An Installation Restoration Program (IRP) was initiated in 1984 with a Phase I Records Search by CH2M Hill (CH2M Hill, 1984). The U.S. Army Corps of Engineers (USACE) was retained in June of 1985 to further delineate groundwater conditions in the East Parking Lot area of Plant 4; the Corps installed six monitoring wells as part of this investigation (U.S. Army Corps of Engineers, 1986). Groundwater sampling in the East Parking Lot area of Plant 4 continues for the purpose of monitoring the TCE plume. The plume has migrated in an easterly to southeasterly direction under the East Parking Lot towards the NAS Fort Worth. The plume extends toward the east with the major branch of the plume following a paleochannel under the flight lines to the south of the Tree system demonstration site. This finger of the plume is being remediated with a pump and treat system. Another branch of the plume appears to follow a paleochannel to the north of the demonstration site. Data indicate that the TCE may have entered the area of the demonstration site along an additional finger of the plume.

Under the USEPA SITE Program, the Phytoremediation system was evaluated for its ability to reduce the mass of

TCE that is transported across the downgradient end of the site (mass flux). Specifically, the following primary performance objectives were established: (1) there would be a 30 percent reduction in the mass of TCE in the aquifer that is transported across the downgradient end of the site during the second growing season, as compared to baseline TCE mass flux calculations, and (2) there would be a 50 percent reduction in the mass of TCE in the aquifer that is transported across the downgradient end of the site during the third growing season, as compared to baseline TCE mass flux calculations. In order to evaluate the primary claim, groundwater levels were monitored and samples were collected and analyzed for TCE concentrations over the course of the study.

In addition to the primary performance objectives, several secondary objectives were evaluated by a team of scientists that were assembled to study the site. Secondary objectives were addressed to help understand the processes that control the ultimate downgradient migration of TCE in the contaminated aquifer, as well as to identify scale-up issues. These secondary objectives include:

- Determine tree growth rates and root biomass
- Analyze tree transpiration rates to determine current and future water usage
- Analyze the hydrologic effects of tree transpiration on the contaminated aquifer
- Analyze contaminant uptake into plant organ systems
- Evaluate geochemical indices of subsurface oxidation-reduction processes
- Evaluate microbial contributions to reductive dechlorination
- Collect data to determine implementation and operation costs for the technology (see Section 3 - Economic Analysis)

4.2 Detailed Description of the Short Rotation Woody Crop Groundwater Treatment System

In April 1996, the U.S. Air Force planted 662 eastern cottonwood trees (*Populus deltoides*) to determine the feasibility of such a planted system to attenuate a part of the TCE-groundwater plume that is migrating beneath the Carswell Golf Course north of Farmers Branch Creek. The following sections discuss the rationale for design decisions related to the Phytoremediation system at the Carswell Golf Course. The monitoring systems that were employed at the Carswell site are also discussed. Monitoring for this demonstration study was more extensive than would be necessary for an applied remediation project because some of the data for this demonstration were collected to help understand the specific processes associated with a SRWCGT System.

4.2.1 Site Selection

Characterization sampling for site selection and system design was completed in January of 1996. Relative groundwater elevations indicated that groundwater in the Terrace Alluvial Aquifer at the selected site generally flows towards the southeast with an average gradient of just over 2 percent. Depth to groundwater (at the time of sampling) ranged from 2.5 to 4 meters (m) below ground surface. Aquifer thickness varied between 0.5 to 1.5 m. Horizontal-hydraulic conductivity values for the aquifer, as determined from eleven slug tests, range from 1 meter/day (m/d) (1.2×10^{-3} centimeters/second (cm/s)) to 30 m/d (3.5×10^{-2} cm/s) with a geometric mean of 6 m/d (7 x 10-3 cm/s). Aquifer porosity, as determined in the laboratory, is 25 percent. Chemical analyses of the groundwater indicated that TCE concentrations ranged from 230 mg/L to 970 mg/L, with cis-1,2-dichloroethene (cis-1,2-DCE) concentrations ranging from 24 mg/L to 131 mg/L. Dissolved oxygen data (> 5mg/L) indicated that the aquifer was well oxygenated (Jacobs Engineering Group Inc. 1996). Furthermore, the ratio of TCE to cis-1,2-DCE from the sampling locations indicated that no significant reductive dechlorination (Chapelle, 1993) had occurred within the selected site. These data suggested that tree roots could reach the water table at the site and that the site would likely benefit from processes that promote reductive dechlorination.

4.2.2 Site Characterization

The eastern cottonwood tree (*Populus deltoides*) was selected for this study on the basis of a literature review, as well as discussions with the Texas Forest Service, the National Resources Conservation Service, and the U.S. Forest Service Hardwood Laboratory. In summary, cottonwoods were selected due to their fast growth, high transpiration rates, and phreatophytic properties. These characteristics allow cottonwoods to rapidly transpire water from a saturated zone and maximize below-ground biomass, which is an important factor in establishing biogeochemical reductive pathways. Other factors that were considered include: (1) tolerance of cottonwoods to the contaminants of concern, (2) the natural occurrence of cottonwoods at the selected site, (3) the perennial nature of cottonwoods, and (4) the longevity of cottonwoods (40 - 100 years).

4.2.3 Size and Configuration of the Tree Plantations

Decisions related to the size and placement of the tree plantations at the demonstration site were critical for ensuring the success of the Phytoremediation system. Factors that were used to determine the size and configuration of the plantations included the general direction of groundwater flow, the extent of groundwater contamination, the volume of groundwater that flowed through the selected site, and the volume of groundwater stored in the aquifer beneath the site.

Two rectangular-shaped plantations that measure approximately 15 by 75 m were established (Figure 4-1). The first plantation was planted with whips, which are sections of one-year old stems harvested from branches during the dormant season. The whips were approximately 0.5 m long at the time of planting and were planted so that approximately 5 centimeters (cm) remained above ground. The second plantation, which was 15 m downgradient, was planted with trees of 2.5 to 3.8 cm caliper (trunk diameter). The caliper trees were just over 2 m tall at the time of planting. The two sizes of trees were selected for inclusion in this study so that differences in rate of growth, contaminant reductions, and cost based on planting strategy could be compared.

The plantations were designed so that the long sides of the plantations are generally perpendicular to the direction of groundwater flow (Figure 4-1). These long sides span the most concentrated portion of the underlying TCE-groundwater plume. The length of the long sides of the plantations was constrained by logistical factors, as well as the experimental nature of the study. The number of trees that were to be planted determined the length of short sides of the rectangular plantations. These short sides are parallel to the direction of groundwater flow. The following information was considered when determining the number of trees that were to be planted:

<u>Volume of Groundwater Flow (Volumetric Flux) Through the Site.</u>
The volumetric flux of groundwater (Q) was calculated according to Darcy's Law:

$$Q = -KiA \qquad \textbf{(Eqn. 4.2-1)}$$

where K is the hydraulic conductivity of the aquifer, i is the hydraulic gradient in the aquifer across the downgradient of the planted area, and A is the cross-sectional area of the aquifer along the downgradient end of the planted area.

<u>Volume of Groundwater in Storage in the Aquifer at the Site.</u>

Volume of groundwater in storage was calculated as follows:

Aquifer Thickness x Study Area Size x Aquifer Porosity **(Eqn. 4.2-2)**

Data assumptions included the following:

- i = 2.25 percent
- A = 75 m^2
- Aquifer thickness is 1m
- Aquifer width is 75 meters
- The aquifer material is a medium sand with mean porosity of 23%.
- K (Horizontal hydraulic conductivity) = 6 m/d (7 x 10^{-3} cm/s)

Using equation 4.2-1 and the above assumptions, groundwater flow (or flux) through the study area was calculated to be approximately 10,125 liters day^{-1} (2,675 gallons day^{-1}). Using equation 4.2-2 and the site dimensions listed in the preceding paragraph, the volume of water in storage in the aquifer beneath the site was calculated to be approximately 776,250 liters (205,060 gallons). It was assumed that the trees would need to transpire a minimum of 10,125 liters (2,675 gallons) of groundwater per day to prevent contaminated water from moving off site during the growing season if no groundwater were released from storage. A greater volume of water would need to be transpired from the aquifer if water were released from storage during the growing season in response to tree transpiration.

According to Stomp (1993), a hybrid poplar tree occupying 4 m^2 of ground can cycle approximately 100 liters day^{-1} (26 gallons day^{-1}) of groundwater under optimal conditions. As a result, it was determined that a minimum of approximately 100 trees would need to be planted at the demonstration site. A total of 662 trees were actually planted. Seven rows of whips were planted approximately 1.25 meters (4 feet) on center in the upgradient plantation for a total of 438 trees and seven rows of caliper trees were planted approximately 2.5 m (8 feet) on center in the downgradient plantation for a total of 224 trees. This is because the estimate of 100 liters day^{-1} per tree is for optimal conditions and field conditions at the site may not always be optimal. It was also expected that some trees would be lost due to natural attrition caused by poor planting, disease and insects. In addition, it was anticipated that some transpired water would be derived from intercepted precipitation, soil moisture or from groundwater released from storage rather than from groundwater flowing into the site across the upgradient end.

4.2.4 Planting and Installation of the Irrigation System

The planting method used in this demonstration is similar to the method used for short rotation wood culture. Whips were obtained from the Texas Forest Service in Alto, Texas; the caliper trees were obtained from Gandy Nursery in Ben Wheeler, Texas. Soil preparation for planting included trenching seven rows in each of the proposed plantations to a depth of one meter. The whips or caliper trees were placed within the trenched rows. Irrigation lines were also placed within the trenches. An agronomic assessment for macro-

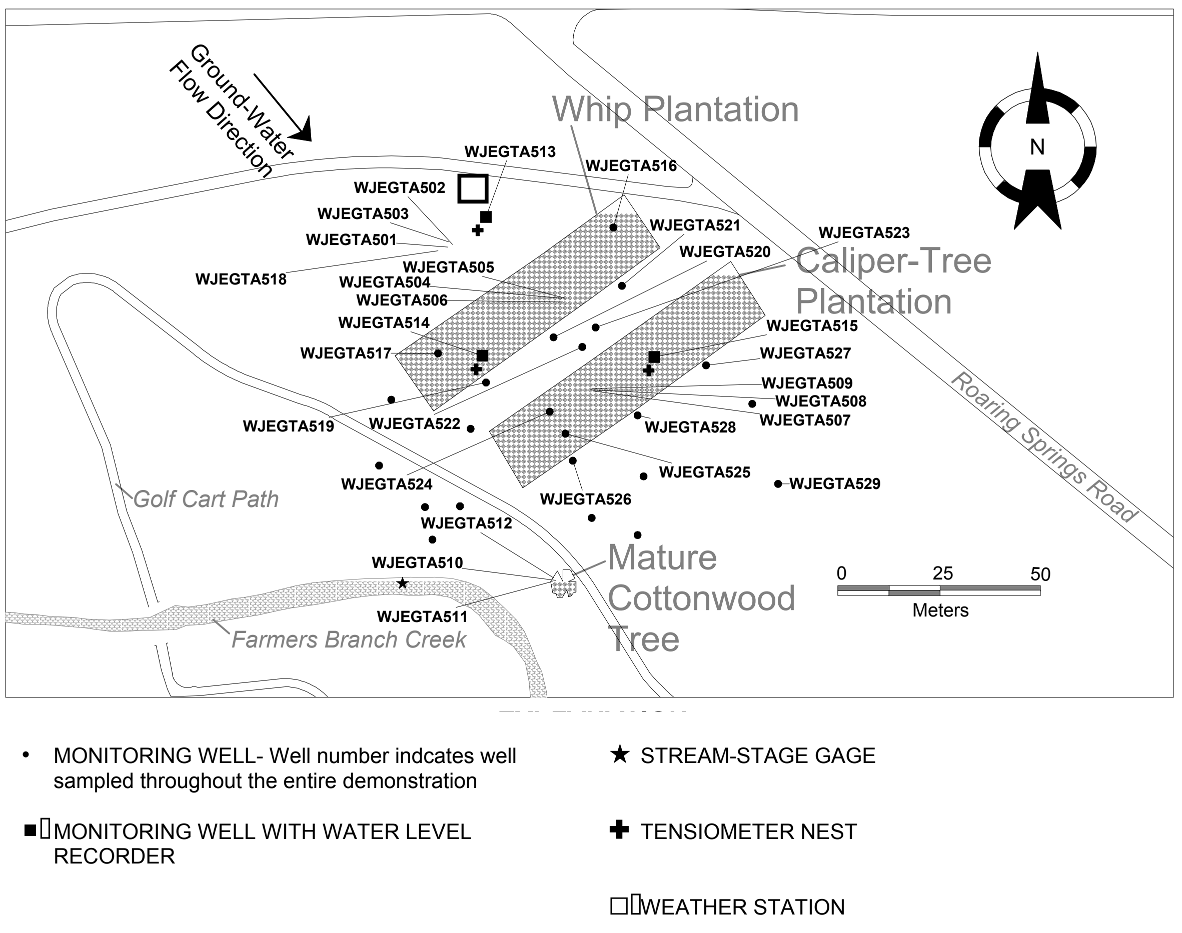


Figure 4-1. Short Rotation Woody Crop Groundwater Treatment System site layout.

and micro-nutrients and the presence or absence of hard pans was conducted. The need for fertilizer was determined from the soil characteristics that were identified through this sampling and analyses, as well as from discussions with the Texas Forest Service, Tarrant County Agricultural Extension Service, and the Texas A&M Horticulture Department. A handful of slow release Osmacote 14-14-14 fertilizer was applied around each whip/caliper tree. When planting was completed, fabric mulch and 10 cm of landscape mulch were placed along each of the planted rows to reduce weed competition. This was especially important for the newly planted whips.

4.2.5 Irrigation

A drip irrigation system was required to supplement precipitation for the first two growing seasons. The trees were watered liberally during this time to encourage deep root development. Data from a precipitation gage at the site were used to help make irrigation decisions. Because the roots were expected to intercept percolating irrigation water (Licht and Madison, 1994), irrigation was not considered to be an additional source of water to the aquifer.

4.2.6 Monitoring

Because the processes associated with Phytoremediation systems require extended time frames to develop, the monitoring system had to be designed to measure small incremental changes in site conditions over time. The monitoring strategy for this demonstration study was more extensive than would be required for a typical Short Rotation Woody Crop Groundwater Treatment System project due to the research nature of the study. Data collected from this intensive monitoring program were used to determine how well the system behaved over time and to develop models to predict future system performance. The following monitoring stations were employed in the study:

- sixty-seven wells installed upgradient, within, downgradient and surrounding the demonstration site, including the area under the mature cottonwood tree near the site
- continuous water level recorders installed in three monitoring wells, including one upgradient of the tree plantations and two within the planted area
- nine tensiometers installed upgradient or within the tree plantations
- a weather station installed to collect site-specific climate data
- a stream gage installed on a creek adjacent to the site to record stream stage
- tree collars and / or tree probes installed periodically during the growing season to measure sapflow in selected trees

Figure 4-1 depicts the location of monitoring points with respect to the tree plantations. A number of wells are not shown on Figure 4-1 because they are outside of the area depicted in the figure. These wells were used to collect groundwater level data surrounding the site for use in calibrating a groundwater-flow model of the area that could be used to help predict out-year performance of the Phytoremediation system.

4.3 Project Objectives

A SRWCGT System was studied to determine the ability of a purposefully-planted tree system to reduce the migration of chlorinated ethene contaminated groundwater. A primary project objective and several secondary objectives were established to provide cost and performance data to determine the applicability and limitations of the technology to similar sites with similar contaminant profiles.

4.3.1 Primary Project Objective

The primary objective of this technology demonstration was to determine how effective the system could be in reducing the mass of TCE in the aquifer transported across the downgradient end of the planted area (TCE mass flux). The following goals were established: (1) the trees will effect a 30 percent reduction in TCE mass flux across the downgradient end of the study area in the second growing season (1997), and (2) the trees will effect a 50 percent reduction in TCE mass flux across the downgradient end of the study area in the third growing season (1998).

It was hypothesized that tree physiological processes would result in the reduction of TCE mass flux in the aquifer due to a combination of hydraulic control of the contaminant plume and in-situ reduction of the contaminant mass (natural pump and treat). Specifically, it was hypothesized that the trees would remove contaminated water from the aquifer by means of their root systems, followed by the biological alteration of TCE within the trees or the transpiration and volatilization of TCE in the atmosphere. The trees would also promote microbially mediated reductive dechlorination of dissolved TCE within the aquifer.

To determine the mass of TCE transported in the aquifer across the downgradient end of the planted area at a given time, the volumetric flux of groundwater across the downgradient end of the site was multiplied by the average of the TCE concentrations in a row of wells immediately downgradient of the site (WJEGTA526 (526), WJEGTA527 (527), WJEGTA528 (528)) (Figure 4-1). The volumetric flux of groundwater was calculated for each event (baseline, peak growing season, late growing season) according to equation 4.2-1 (presented in section 4.2.3).

The following assumptions applied:

- Horizontal-hydraulic conductivity was assumed to be constant over the course of the study because measurements were made in the same locations. A value of 6 m/d was used and represents the geometric mean for the study area.

- The hydraulic gradient across the downgradient end of the planted area at selected times was calculated using groundwater elevation data from monitoring wells 522 and 529 (Figure 4-2). Well 522 is located between the tree stands near the center of the planted area. Well 529 is downgradient and outside the influence of the trees. These wells were chosen so that they did not reflect increases in the hydraulic gradient across the upgradient end of the site. A corresponding potentiometric-surface map for each selected time was consulted to verify that changes in hydraulic gradient were due to the influence of the trees rather than to changes in the direction of groundwater flow.

- The thickness of the saturated zone at the selected times was calculated from the average thickness of the aquifer in the monitoring wells immediately downgradient of the tree plots (wells 526, 527, and 528) (Figures 4-1 and 4-2). The saturated thickness in each of these three wells was first normalized to wells in the surrounding area to account for temporal changes in the saturated thickness of the aquifer unrelated to the planted trees. Specifically, the water-level data for these wells were adjusted by an amount equal to the difference between the water level at the selected time and the water level at baseline (November 1996) in wells outside the influence of the planted trees. (November 1996 was used to represent baseline conditions in the aquifer because the most comprehensive set of water-level and ground-water chemistry data for the period before the tree roots reached the water table were collected at this time.)

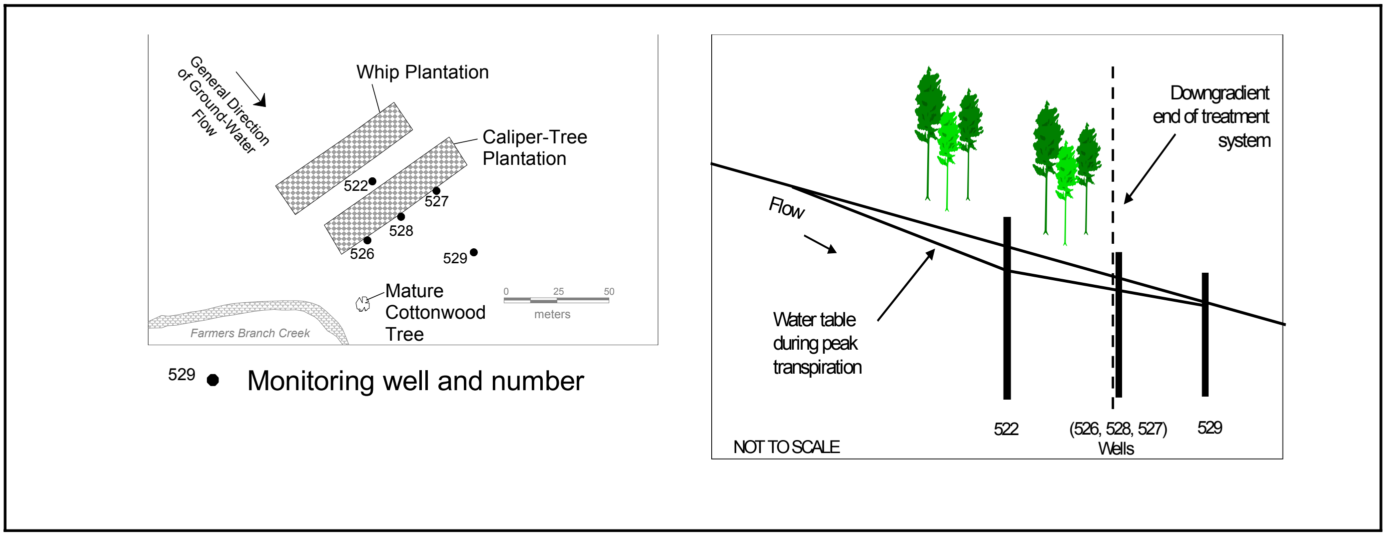


Figure 4-2. Wells used to monitor for changes in the volumetric flux of groundwater across the downgradient end of the Short Rotation Woody Crop Groundwater Treatment system.

- The aquifer width that was used in the volumetric-flux calculations is 70 m, which is the approximate length of the tree plantations.

The mass flux across the downgradient end of the planted area was subsequently calculated for the various events (baseline, peak growing season, late growing season) according to the following formula:

$$M_f = Q(C) \qquad \textbf{(Eqn. 4.3-1)}$$

where Q is the volumetric flux of groundwater and C is the average TCE concentration in wells 526, 527, and 528 (immediately downgradient of the planted area) for each event.

The following formula was then used to calculate the percent change in the mass flux of TCE at selected times that can be attributed to the planted trees:

$$\Delta M_f(event\ x) = \frac{M_f(baseline) - M_f(event\ x)}{M_f(baseline)} (100)$$

(Eqn. 4.3-2)

Where:

Event x is peak (late June or beginning of July) of the growing season 1997, 1998, or 1999, or late (end of September or beginning of October) in the growing season 1997 or 1998.

4.3.2 Secondary Project Objectives

Secondary objectives were included in the study to elucidate the biological, hydrological, and biochemical processes that contribute to the effectiveness of a SRWCGT system on shallow TCE-contaminated groundwater. Since a SRWCGT system can take several years to become fully effective, much of the data associated with the secondary objectives were collected to build predictive models to determine future performance. Measurements were primarily related to tree physiology (tree growth, tree transpiration, contaminant translocation) and aquifer characteristics (hydraulic, geochemical, microbiological). Scientists at Science Applications International Corporation (SAIC), University of Georgia, U.S. Forest Service, USEPA, and USGS conducted the work related to the secondary project objectives in cooperation with ASC/ENV and the USEPA SITE program.

Secondary objectives and the scope of the associated data collection are described below:

Determine tree growth rates and root biomass: Above-ground biomass growth was measured over the course of the study to assess the rate-of-growth of the whip and caliper-tree plantations. Fifty-two whips and fifty-one caliper-trees were evaluated for the following parameters: (1) trunk diameter, (2) tree height, and (3) canopy diameter. The measurements were taken during the following sampling events: (1) December 1996, (2) May 1997, (3) July 1997, (4) October 1997, (5) June 1998, and (6) October 1998. An additional investigation was undertaken to quantify below ground biomass and the extent of the root system in September of 1997. This information was used to understand the establishment of the root system, which is the primary means for targeting the contaminants in the aquifer. Differences in root characteristics between the whip plantings and the more expensive caliper-tree plantings were also investigated. Eight trees (four from each plantation) were examined.

Analyze tree transpiration rates to determine current and *future water usage:* An important remediation mechanism of the planted system is the interception and removal of water from the contaminated aquifer. Measured transpiration rates can provide information that is critical for evaluating current removal of water from the aquifer (saturated zone) and for predicting future water usage. Transpiration rates were quantified for the whips and the caliper-tree plantings, as well as for several mature trees proximal to the study area. Sapflow, leaf conductance, and pre-dawn and mid-day leaf water potential were measured on 14 to 16 trees from May through October in 1997 and 1998. Climate data were also collected at the site and used in conjunction with the transpiration data to model future tree transpiration.

Analyze the hydrologic effects of tree transpiration on the contaminated aquifer: The removal of contaminated water from the aquifer at the Carswell Golf Course site has the potential to alter the local groundwater flow system, resulting in some hydraulic control of the contaminant plume. Hydraulic control may be one of the principal mechanisms related to reduction in TCE mass flux across the downgradient end of the planted system. Groundwater level data were collected and used to assess the hydrologic effects of the cottonwood trees on the contaminated aquifer. Specifically, data were collected in up to 62 wells during November and December 1996; May, July, and October 1997; February, June, and September 1998; and June 1999. In addition, groundwater levels were measured every 15 minutes in three wells to record seasonal fluctuations in groundwater levels over the course of the study. Beginning in summer 1998, the stage in Farmers Branch Creek was also recorded every 15 minutes so that the hydrologic effects of the trees could be isolated from other temporal changes in the system. Slug tests were conducted in eleven wells to determine the site-specific hydraulic conductivity of the aquifer. Eleven core samples were collected and analyzed in the laboratory to determine site-specific aquifer porosity. These data, along with the transpiration data, were used to model future hydrologic effects of the planted trees on the contaminated aquifer.

Analyze contaminant uptake into plant organ systems: A potential removal mechanism for TCE and other volatile contaminants in the aquifer is translocation of the contaminants into the plant organs. Chlorinated ethenes may be transpired through the stomata of the leaves or metabolized within the plant organs to other compounds such as simple haloacetic acids (N. Lee Wolf, U.S.EPA, written communication 1999). To assess the presence and magnitude of contaminant uptake and translocation at the study area, plant organ samples of roots, stems, and leaves were acquired and analyzed for volatile organic compounds. Samples were taken from five whip plantings, five caliper-tree plantings, a mature naturally-occurring cottonwood, and a naturally-occurring mesquite tree. The trees were sampled during the following events: (1) October 1996 - end of the first growing season, (2) July 1997 - peak of the second growing season, (3) October 1997 - end of the second growing season, (4) June 1998 - peak of the third growing season, and (5) October 1998 - end of the third growing season. Tree cores were collected from 11 species of trees surrounding the planted area and analyzed for the presence of TCE and cis-1,2-DCE in September 1998. In addition, leaves from seven trees (cottonwood whip, cottonwood caliper tree, cedar, hackberry, oak, willow, mesquite) were collected and analyzed for dehalogenase activity to determine whether the leaves had the capability to break down TCE.

Evaluate geochemical indices of subsurface oxidation-reduction processes: Many TCE contaminated aquifers could benefit from microbially-mediated reductive dechlorination. Reductive dechlorination, however, cannot take place under the aerobic conditions that are present at many such shallow sites, where TCE is the sole contaminant. Processes that promote the consumption of oxygen in the subsurface can accelerate the microbial reductive dechlorination process. Trees can promote subsurface oxygen utilization by providing the subsurface environment with organic matter that stimulates aerobic microbial activity that can result in depleted oxygen levels and resulting anaerobic conditions. Groundwater geochemical samples were collected at the study area to assess the development of an anaerobic subsurface environment over time, along with any associated reductive dechlorination of the chlorinated ethenes. Samples were collected from both the groundwater and the unsaturated soil throughout the study area. Groundwater analyses included chlorinated volatile organic compounds (VOCs, including TCE and cis-1,2-DCE), dissolved organic carbon, methane, sulfide, ferrous and total iron, dissolved oxygen, and dissolved hydrogen. Soil measurements (unsaturated zone) included total organic carbon and pH.

Evaluate microbial contributions to reductive dechlorination: A microbial survey was performed at the study area to determine if the planted trees have driven the local microbial community structure to support reductive dechlorination of TCE. Samples of soil and groundwater were collected from thirteen locations in February and June of 1998. Microbial concentrations were determined using a five-tube Most Probable Number (MPN) analysis. Enumerations were performed to determine the populations of the following types of microorganisms: aerobes, denitrifiers, fermenters, iron-reducers, sulfate reducers, total methanogens, acetate-utilizing methanogens, formate-utilizing methanogens, and hydrogen-utilizing methanogens. Laboratory microcosms were also established to estimate biodegradation-rate constants for the demonstration site.

4.4 Performance Data

The following sections present a discussion of the technology's performance with respect to the primary and secondary project objectives. The purpose of the following sections is to present and discuss the results specific to each objective, provide an interpretive analysis from which the conclusions are drawn, and, if relevant, offer alternative explanations and viewpoints.

4.4.1 Summary of Results - Primary Objective

The primary objective of the study was to determine the Phytoremediation system's ability to reduce the mass flux of TCE across the downgradient end of the site during the second (1997) and third (1998) growing season. The objective called for a 30 percent reduction during the second growing season and a 50 percent reduction during the third growing season. The objective could be achieved from a combination of the two mechanisms hypothesized to be capable of contaminant reduction - hydraulic control and in-situ reductive dechlorination.

Table 4-1 presents the results of the calculations used to validate the primary claims described in equations 4.2-1, 4.3-1, and 4.3-2. The SRWCGT system did not achieve the mass flux reductions of 30 and 50 percent for the second and third growing seasons, respectively. The TCE mass flux was actually up 8 percent during the peak of the second growing season, as compared to baseline conditions. The planted trees reduced the outward flux of groundwater by 5 percent during the peak of the second season but TCE concentrations in the row of wells immediately downgradient of the trees were higher, resulting in the increase in TCE mass flux. These data suggest that the mass flux of TCE out of the planted area during the peak of the second season would have been even greater in the absence of the hydraulic influence of the trees. The TCE mass flux during the third growing season was down 11 percent at the peak of the season and down 8 percent near the end of the season, as compared to baseline conditions. Concentrations of TCE during the third season in the row of downgradient wells were similar to concentrations at baseline and the reduction in TCE mass flux is primarily attributed to a reduction in the volumetric flux of groundwater out of the site. The flux of groundwater out of the site during the peak of the fourth growing season was 8 percent less than at baseline. Groundwater was not sampled for TCE concentrations at this time. Variations in climatic conditions are the likely explanation for the differences in the outward flux of groundwater between the third and fourth seasons. In general, these data reveal that the system had begun to influence the mass of contaminants moving through the site during the three-year demonstration.

The contributions of hydraulic control and reductive dechlorination as attenuation mechanisms can be evaluated from the study results. The principle mechanism for the reductions in mass flux observed during the early stage of the system's development was hydraulic control. TCE concentrations from the downgradient row of wells did not decrease during the first three growing seasons, which indicates that reductive dechlorination processes had not yet significantly occurred (Table 4-1). Although TCE concentrations had not decreased, there was a reduction in the mass of TCE in the plume just downgradient of the study area because tree transpiration had affected the volumetric flux of contaminated water out of the site. This is evidenced by the decrease in the hydraulic gradient across the downgradient end of the planted area, as well as the decrease in saturated thickness of the aquifer at the downgradient end of the site. The largest observed reduction in hydraulic gradient was 10 percent (0.0159 to 0.0143) and occurred during June 1998. The maximum drawdown that could be attributed to the trees during June 1998 is 10 cm and was observed between the two tree plots. Although a drawdown cone could be mapped at the water table at this stage of the system's development, there remained a regional hydraulic gradient across the site that resulted in most of the contaminated groundwater flowing outward across the downgradient end of the planted area (Figure 4-3).

A ground-water flow model of the demonstration site was constructed using MODFLOW (McDonald and Harbaugh, 1988) to help in understanding the observed effects of tree transpiration on the aquifer (Eberts, et. al. In Press). The model illustrates that the volume of water that was transpired from the aquifer during 1998 was greater than the reduced outflow of groundwater that can be attributed to the trees. This is because of an increased amount of groundwater inflow to the demonstration site due to an increase in hydraulic gradient on the upgradient side of the drawdown cone created by the trees. The amount of contaminated water that was transpired from the aquifer during the peak of the 1998 growing season (third season) was equal to an amount that is closer to 20 percent of the initial volumetric flux of water through the site rather than the observed decrease in outflow of 12 percent.

Greater hydraulic control is anticipated in the future because the trees did not reach their full transpiration potential during the time period of the demonstration study. Predictions for out-year hydraulic control will be discussed in greater detail in section 4.4-2.

4.4.2 Summary of Results - Secondary Objectives

In addition to providing the data necessary to evaluate the primary claim, the demonstration project included several studies designed to address secondary project objectives. Results of these studies provide insight into the SRWCGT System's contaminant-reduction mechanisms. Since a Tree system may take several years to become established, special attention was given to the derivation of

Table 4-1. Summary of Primary Objective Results [m, meter; d, day;µg, microgram; L, liter; g, gram] (See Appendix C)

Event	Hydraulic Gradient Across Downgradient End of Planted Area[a]	Cross Sectional Area Along Downgradient End of Planted Area[b] (m^2)	Volumetric Flux of Groundater Across Downgradient End of Planted Area[c] (m^3/d)	Change in Voumetric Flux Across Downgradient End of Planted Area Attibuted to Planted Trees (%)	Average TCE Concentration in Wells Along Downgradient End of Planted Area[d] (µg/L)	Mass Flux of TCE Across Downgradient End of Planted Area (g/d)	Change in Mass Flux of TCE Across Downgradient End of Planted Area Attributed to Planted Trees (%)
Baseline (1996)	0.0159	84	8.0	--	469	3.8	-
Peak[e] 2nd Season (1997)	0.0154	82	7.6	-5%	535	4.1	8%
Late[e] 2nd Season (1997)	0.0157	83	7.8	-2%	-	-	-
Peak 3rd Season (1998)	0.0143	82	7.0	-12%	483	3.4	-11%
Late 3rd Season (1998)	0.0150	83	7.5	-6%	473	3.5	-8%
Peak 4th Season (1999)	0.0153	81	7.4	-8%	-	-	-

[a] Gradient calculated between monitoring wells 522 and 529.

[b] An aquifer width of 70m was used for the aquifer cross-sectional area calculations; aquifer thickness was the average of the saturated thickness in wells 526, 527, and 528 normalized to wells from the surrounding area to account for seasonal water table fluctuations unrelated to the planted trees.

[c] A horizontal hydraulic conductivity of 6 m/day was used for the volumetric flux calculations. This is the geometric mean of the hydraulic conductivity values determined for the study area.

[d] TCE concentration is the average in wells 526, 527 and 528.

[e] Peak growing season is end of June or beginning of July. Late growing season is end of September or beginning of October.

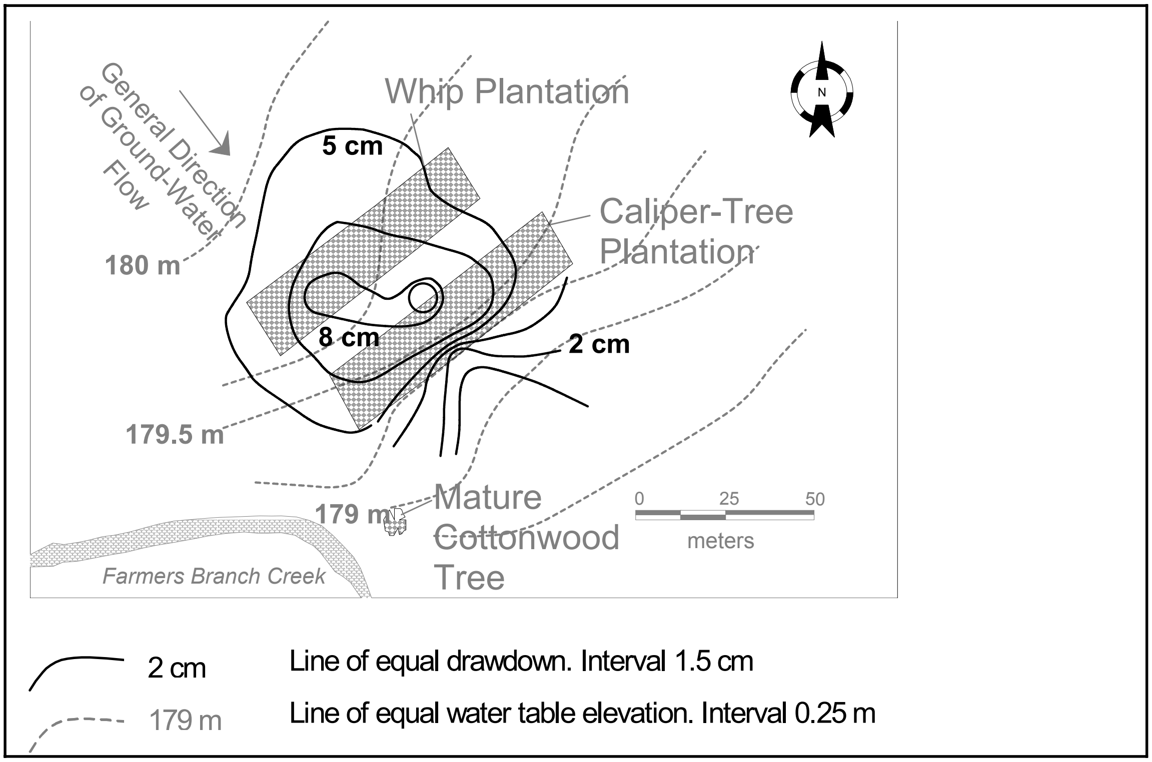


Figure 4-3. Drawdown at the water table that can be attributed to the trees, June 1998.

parameters that could be used to model future performance. In addition, a mature cottonwood tree located proximal to the planted trees provided valuable information related to the upper bounds of contaminant reduction.

Determine tree growth rates and root biomass

The rate of tree growth (above- and below- ground) was important for determining the progression of the SRWCGT system over time. Above-ground biomass, especially leaf area, controls transpiration rates and the ability of such a system to influence groundwater hydrology. The growth of the below-ground organs (roots) controls a system's efficiency for extracting water from the aquifer (saturated zone).

Fifty-two whips and fifty-one caliper trees were measured for trunk diameter, tree height, and canopy diameter in December 1996, May 1997, July 1997, October 1997, June 1998, and October 1998 by employees of SAIC. Figures 4-4 through 4-6 graphically depict the physical changes in the whip and caliper-tree plantations over time. Figure 4-7 is a photograph of the caliper-tree plantation at the time of planting (April 1996). Figure 4-8 is a photograph of the caliper-tree plantation at the end of the third growing season (October 1998).

Overall, both plantations grew well and significantly increased in all physical parameters measured over the course of the study. Only two of the fifty-two whips and three of the fifty-one caliper trees did not survive to the end of the study. (Some of the other trees in the plantations, however, were temporarily stunted by beaver activity during the study.) In terms of trunk diameter, both plantations increased over time; 1.41 cm to 5.13 cm for the whips, and 3.83 to 8.12 cm for the caliper trees. Tree height also significantly increased for both plantations. In December of 1996, tree height for the whips averaged 2.27 m and 3.77 m for the caliper trees. In September of 1998, average tree height for the whips was 5.52 m and 6.64 m for the caliper trees. Although the caliper trees were taller during the first growing season, the whips were able to approach the height of the caliper trees by the end of the third growing season. For the canopy diameter, both the whips and caliper trees increased over time, however, there were minor differences between the plantations over time.

Canopy diameter is an important parameter that controls leaf area and transpiration. In an open growth environment, canopy diameter is dependent on the overall growth and maturation of the tree. In a designed plantation, individual trees are planted in rows at a specified spacing. As the trees grow, the canopies of individual trees can touch, which slows down further growth due to competition for light. This limits the maximum stand-level transpiration attainable for individual trees, however, it does not affect the maximum amount of water that can be transpired by the whole plantation if the tree spacing is such that a closed canopy eventually will be achieved. Trees in the whip plantation were planted approximately 1.25 m apart. The average canopy diameter for the whips at the end of September 1998 (end of the third growing season) was 2.32 m. The whip plantation was approaching canopy closure at this time. Trees in the caliper-tree plantation were planted approximately 2.50 m apart. The average canopy diameter for the caliper trees in September of 1998 was 2.52 m. The caliper-tree plantation was not approaching canopy closure at this time.

Root biomass and extent were examined in September of 1997 in the whip and caliper-tree plantations. Four trees from each plantation were evaluated for fine root biomass and length, coarse root biomass, and root distribution. Differences in the fine root biomass between the plantations were not statistically significant: 288 g m^{-2} for whips vs. 273 g m^{-2} for caliper trees in the <0.5 mm range; 30 g m^{-2} for whips vs. 36 g m^{-2} for the caliper trees in the 0.5 to 1.0 mm range; and 60 g m^{-2} for the whips vs. 91 g m^{-2} for the caliper trees in the 1.0 to 3.0 mm range. Fine root length density in the upper 30 cm of soil was statistically greater in the caliper trees as compared to the whips (8942 m m^{-2} vs. 7109 m m^{-2}). Coarse root mass was significantly greater in the caliper trees in the 3.0 to 10 mm range; 458 g $tree^{-1}$ vs. 240 g $tree^{-1}$. Although the coarse root mass in the > 10mm range was also greater in the caliper trees than in the whips; the difference in this range was not statistically significant. Details of this root study can be found in a report entitled, “Root Biomass and Extent in Populus Plantations” (Hendrick, 1998).

At this point in the second growing season (September 1997), the roots of both the whips and caliper trees had reached the water table (275 cm for the whips and 225 cm for the caliper trees), and the depth distribution of the roots was quite similar (Figure 4-9). In other words, the more expensive planting costs of the caliper trees did not appear to impart any substantial benefit with regards to root depth and biomass. Observed differences between the whips and the caliper trees were reported to be due as much to inherent genotypic differences as to the different modes of establishment.

Analyze tree transpiration rates to determine current and future water usage

Transpiration is the evaporative loss of water from a plant. Water transport mechanisms move water from the soil zone to the stomata of the leaf where it is lost to the atmosphere. Transpired water can be derived from the near surface soils, and in the case of phreatophytic species, from the saturated zone (aquifer). The ability of phreatophytic species to seek and use contaminated groundwater is the basis of this system technology. The amount of water transpired by trees throughout their life cycle is an important factor in

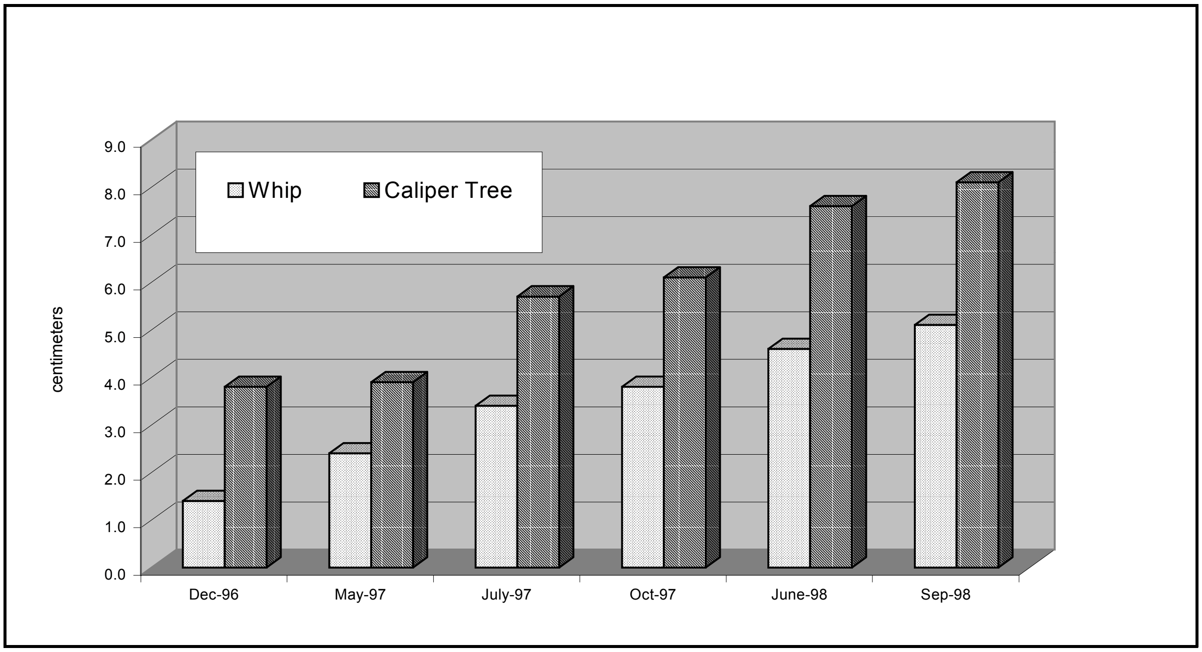


Figure 4-4. Trunk diameter over time.

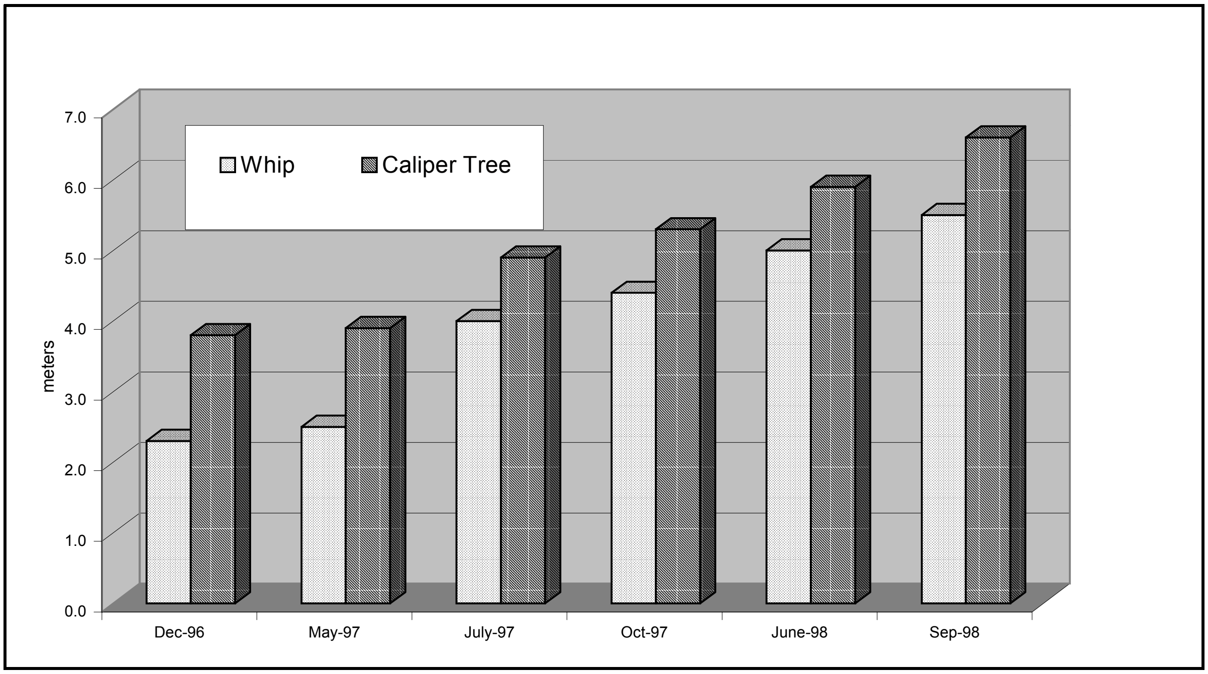


Figure 4-5. Tree height over time.

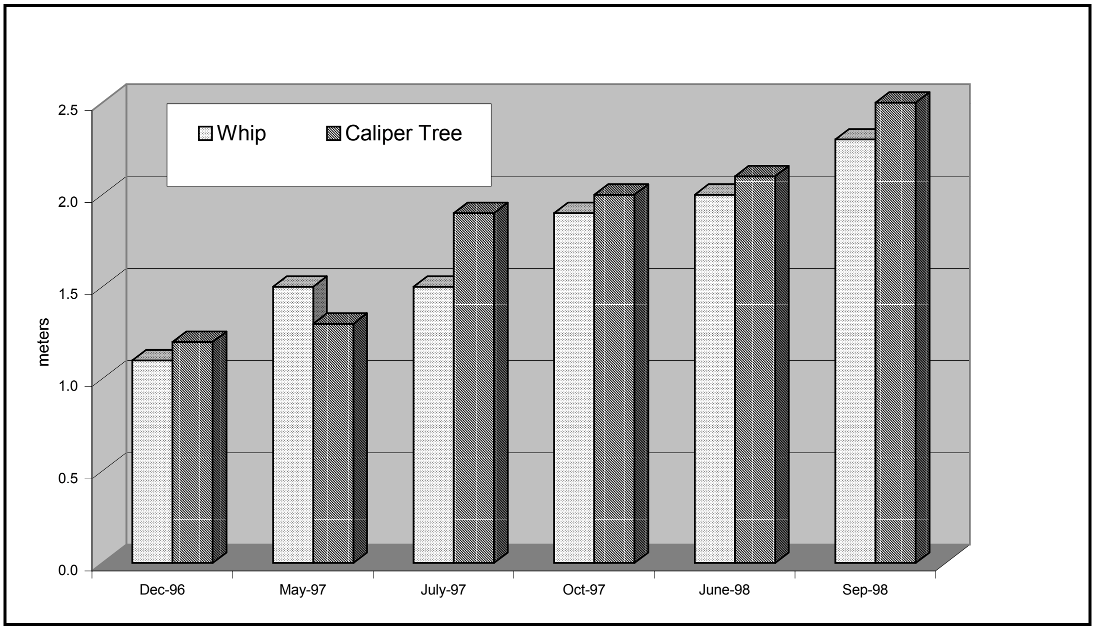


Figure 4-6. Canopy diameter over time.

Figure 4-7. Caliper-tree plantation at the time of planting, April 1996.

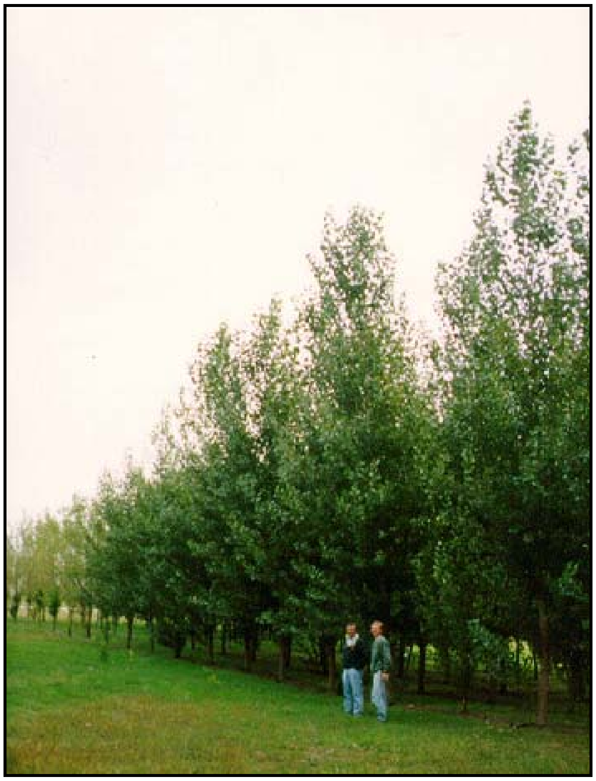


Figure 4-8. Caliper-tree plantation at the end of the third growing season, October 1998.

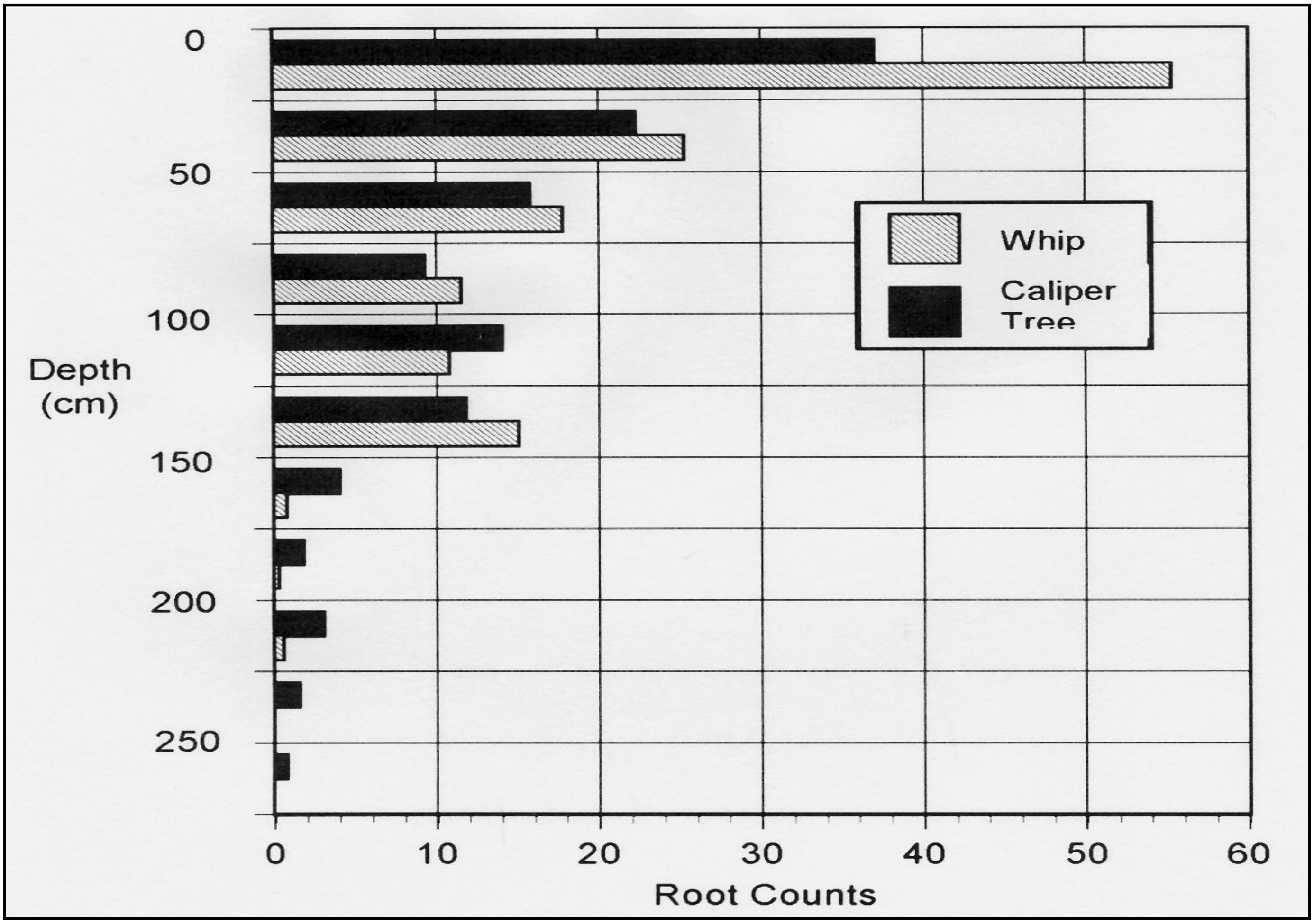


Figure 4-9. Root counts by depth.

determining the effectiveness of the technology for containment and remediation of a contaminant plume. Transpiration rates can be used in conjunction with other site-specific characteristics (climate, soil type, hydrology) to determine water use patterns and to help determine process effectiveness, including future performance.

Scientists from the USDA Forest Service, Cowetta Hydrologic Laboratory, conducted a transpiration study at the demonstration site. Specifically, transpiration measurements were taken on a statistical sampling of whips and caliper trees in May, June, July, August, and October of 1997. In addition, transpiration was measured on six mature trees in the vicinity of the study area in May, July, and September of 1998. Transpiration measurements on individual trees were extrapolated to estimate stand-level transpiration rates. The sapflow data were used to (1) compare transpiration rates for the two planting strategies (whips vs. caliper trees), (2) investigate variability over the growing season, and (3) determine stand-level water usage over the entire growing season. Data from the mature trees was used to estimate upper-bound levels of transpiration that may be attainable by the Phytoremediation system in the future. The transpiration measurements are summarized in a report entitled “Leaf Water Relations and Sapflow in Eastern Cottonwoods (Vose et al., 2000).

The greatest sapflow in the planted trees occurred in June, while the lowest occurred in the month of October. In general, sapflow was significantly greater in individual caliper trees than in individual whips for all months except October (Figure 4-10a).

The average seasonal sapflow for the caliper trees was almost two times greater than that of the whips (0.61 kg hr^{-1} $tree^{-1}$ vs. 0.34 kg hr^{-1} $tree^{-1}$). Because the whips were considerably smaller than the caliper trees, the investigators also expressed sapflow on a per unit basal area basis (kg cm^{-2} hr^{-1}). When expressed this way, rates were generally greater in the whips than in the caliper trees (0.033 kg cm^{-2} hr^{-1} vs. 0.027 kg cm^{-2} hr^{-1}) (Figure 4-10b).

Mean total daily transpiration rates were also determined. Mean total daily transpiration for the whips ranged from 9.2 kg $tree^{-1}$ day^{-1} (2.4 gallons $tree^{-1}$ day^{-1}) in June to 1.6 kg $tree^{-1}$ day^{-1} (0.42 gallons $tree^{-1}$ day^{-1}) in October. Mean

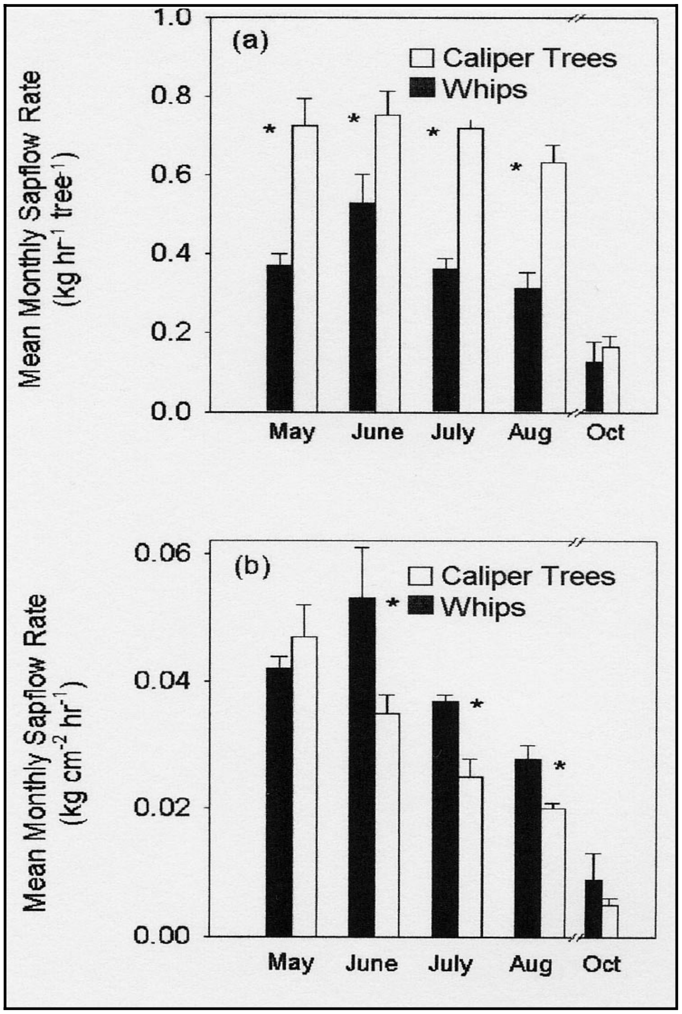


Figure 4-10. Variation in mean hourly sapflow rate (a) expressed on a per tree basis and (b) expressed on a per unit basal area basis. Data are sample period means for all months ($p<0.05$) differences between whips and caliper trees are denoted by *. Vertical lines on all bars represent standard errors.

total daily transpiration for the caliper trees ranged from 14.7 kg tree^{-1} day^{-1} (3.89 gallons tree^{-1} day^{-1}) in July to 0.92 kg tree^{-1} day^{-1} (0.24 gallons tree^{-1} day^{-1}) in October.

Preliminary estimates of stand-level transpiration were extrapolated from these total daily mean transpiration values by assuming that the amount of sapflow measured in the sample trees represents the population. The stand-level estimates indicate that there was very little difference in the amount of water transpired from the whip plantation and the caliper-tree plantation during the second growing season. This is because the planting density of the whips is nearly twice that of the caliper trees. When sapflow values were averaged across the second growing season, sapflow was 16,637 kg ha^{-1} day^{-1} for the caliper trees, and 15,560 kg ha^{-1} day^{-1} for the whips. Because each plantation measures approximately 75 by 15 meters (0.1125 hectares), the total average daily transpiration was estimated at 1,872 liters day^{-1} (494 gallons day^{-1}) for the caliper-tree plantation and 1,750 liters day^{-1} (462 gallons day^{-1}) for the whip plantation. These amounts correlate with an estimated loss of water through transpiration from the study area of approximately 3,600 liters day^{-1} (950 gallons day^{-1}) during the second growing season. Total estimated growing season transpiration for the second season was estimated to be approximately 25 cm. It was noted that this amount of transpiration is about one-third to one-half of the amount of transpiration for mature hardwood forests in other regions of the U.S. (Vose and Swank, 1992), which indicates that substantially greater transpiration will occur as the planted trees mature.

The sapflow rate that was measured for the mature cottonwood tree adjacent to the planted site was as high as 230 kg day^{-1} (~60 gallons day^{-1}). This value represents an upper limit of potential transpiration by a single tree at the demonstration site. This rate, however, is non-attainable in a plantation configuration. As previously discussed, canopy closure in the whip and caliper-tree plantations will eventually limit leaf area and thereby the maximum potential transpiration of individual trees. As a result, the spacing of the trees in the SRWCGT system at the demonstration site will affect the amount of water that individual trees will transpire, but should not affect the amount of water that will be transpired by the overall plantations as long as canopy closure is eventually achieved. Tree spacing will, however, affect the timing of canopy closure. The full report on "Sap Flow Rates in Large Trees at the Carswell Naval Air Station" can be found in the report entitled the same (Vose and Swank, 1998).

Because the planted trees were not expected to reach their transpiration potential during the period of demonstration, a modeling approach was necessary to predict future system performance at the demonstration site. Site-specific climate, sapflow, soil-moisture, and tree-root data were used to parameterize and validate the physiologically-based model PROSPER (Goldstein and others, 1974), which was then used to predict the amount of evapotranspiration at the site that will likely occur once the plantations have achieved a closed canopy (maximum transpiration). Predictions vary according to assumptions made regarding future climatic conditions, as well as soil moisture and root growth. Predicted stand-level evapotranspiration for the period when the tree plantations have achieved a closed canopy (year 12 and beyond) is the same for whips and caliper trees and ranges from 25 to 48 cm per growing season, depending on model assumptions. The root biomass study (Hendrick, 1998) was conducted to help determine the percent of this transpired water that may be derived from the contaminated aquifer (saturated zone). Predicted transpiration from the aquifer ranges from 12 to 28 cm per growing season for year 12 and beyond, depending on model assumptions; this is 48 to 58 percent of predicted total evapotranspiration. The effects of this amount of transpiration on the groundwater flow system in the study area are discussed in the next section.

Analyze the hydrologic effects of tree transpiration on the contaminated aquifer

The ground-water flow model that was constructed to help in understanding the observed effects of tree transpiration on the aquifer was also used to predict the effects of future increases in transpiration rates on the volumetric flux of groundwater across the downgradient end of the planted area by incorporating the predictions of future transpiration from the saturated zone made by use of the hydrologic model PROSPER. Hydrologists with the USGS used the groundwater flow code MODFLOW to construct the groundwater flow model and to make the volumetric flux predictions. Site-specific data on aquifer characteristics, groundwater levels, and stream stage, as well as stream discharge measurements reported in Rivers and others (1996) were used to calibrate the groundwater flow model to both steady state and transient state conditions before the model was used to make predictions. (One lesson learned during collection of continuous water-level data for construction of this model is that tree roots grow through well screens and entangle downhole instrumentation, which can lead to loss of data. Sites need to be checked frequently and wells need to be reamed periodically to remove roots.)

The groundwater flow model was used to predict the magnitude and extent of the drawdown cone that may be expected as a result of future transpiration at the study area. A volumetric groundwater budget was computed for each predictive simulation. Because the PROSPER model predictions simulate a range of possible climatic conditions, as well as soil-water availability and root growth scenarios, there is a range of predicted drawdown and predicted reductions in the outflow of groundwater from the planted area. Predicted drawdown during peak growing season after the trees have achieved a closed canopy (year 12 and beyond) ranges from 12 to 25 cm at the center of the drawdown cone. The diameter of the predicted drawdown cone ranges from approximately 140 m to over 210 m (Figures 4-11 and 4-12).

These drawdown predictions are associated with a predicted decrease in the volumetric flux of groundwater across the downgradient end of the planted area that ranges from 20 to 30 percent of the volumetric flux of water through the site before the trees were planted. The predicted volume of water transpired from the aquifer in future years when maximum transpiration has been reached ranges from 50 to 90 percent of the initial volumetric flux of groundwater at the site. The discrepancy between the reduction in the volumetric outflow of groundwater and the volume of water transpired from the aquifer can be attributed to the combined increase in hydraulic gradient on the upgradient side of the drawdown cone, which leads to an increase in groundwater inflow to the site, and the release of water from storage in the aquifer (Figure 4-13).

These model results indicate that a regional hydraulic gradient will remain across the planted area during future growing seasons. The volumetric flux of groundwater across the downgradient end of the planted area, however, will be notably reduced. Percent reductions in the TCE mass flux due to tree transpiration will be somewhat less than reductions in the volumetric flux of groundwater because membrane barriers at the root surface prevent TCE from being taken up at the same concentration as it occurs in the groundwater. The transpiration stream concentration factor or fractional efficiency of uptake for TCE has been reported to be 0.74 (Schnoor, 1997). No hydraulic control of the plume is predicted for the dormant season (November through March). Additional information on the hydrologic effects of cottonwood trees can be found in the report entitled "Hydrologic effects of cottonwood trees on a shallow aquifer containing trichloroethene" (Eberts et al., 1999).

It may be possible to achieve a greater amount of hydraulic control if more trees are planted but increased groundwater inflow and release of water from storage in the aquifer will continue to be factors that affect hydraulic control of the contaminant plume. It is also possible that full hydraulic control of the plume would not be desirable if the demonstration project were scaled up because full control may result in an unacceptable decrease in flow in Farmers Branch Creek, particularly since hydraulic control is only one mechanism that contributes to the cleanup of a groundwater plume at a phytoremediation site. A solute transport model of the groundwater system at the study area is being constructed to gain insight into the relative importance of various attenuation mechanisms associated with Tree systems - hydraulic control, reductive dechlorination, and sorption.

Analyze contaminant uptake into plant organ systems

During the period of demonstration, employees of SAIC collected plant tissue samples from the whips, caliper trees, and the mature cottonwood tree five times (October 1996, July 1997, October 1997, June 1998, and October 1998). Specifically, leaf and stem (new growth) samples were taken from five whips, five caliper trees, and the mature cottonwood tree during each sampling event. Root samples were collected from the whip and caliper-tree plantations during the October 1996 and June 1998 sampling events. The samples were analyzed for volatile organic compounds (VOCs). The purpose of these analyses was to determine (1) if volatile compounds (especially chlorinated VOCs) were present in the plant

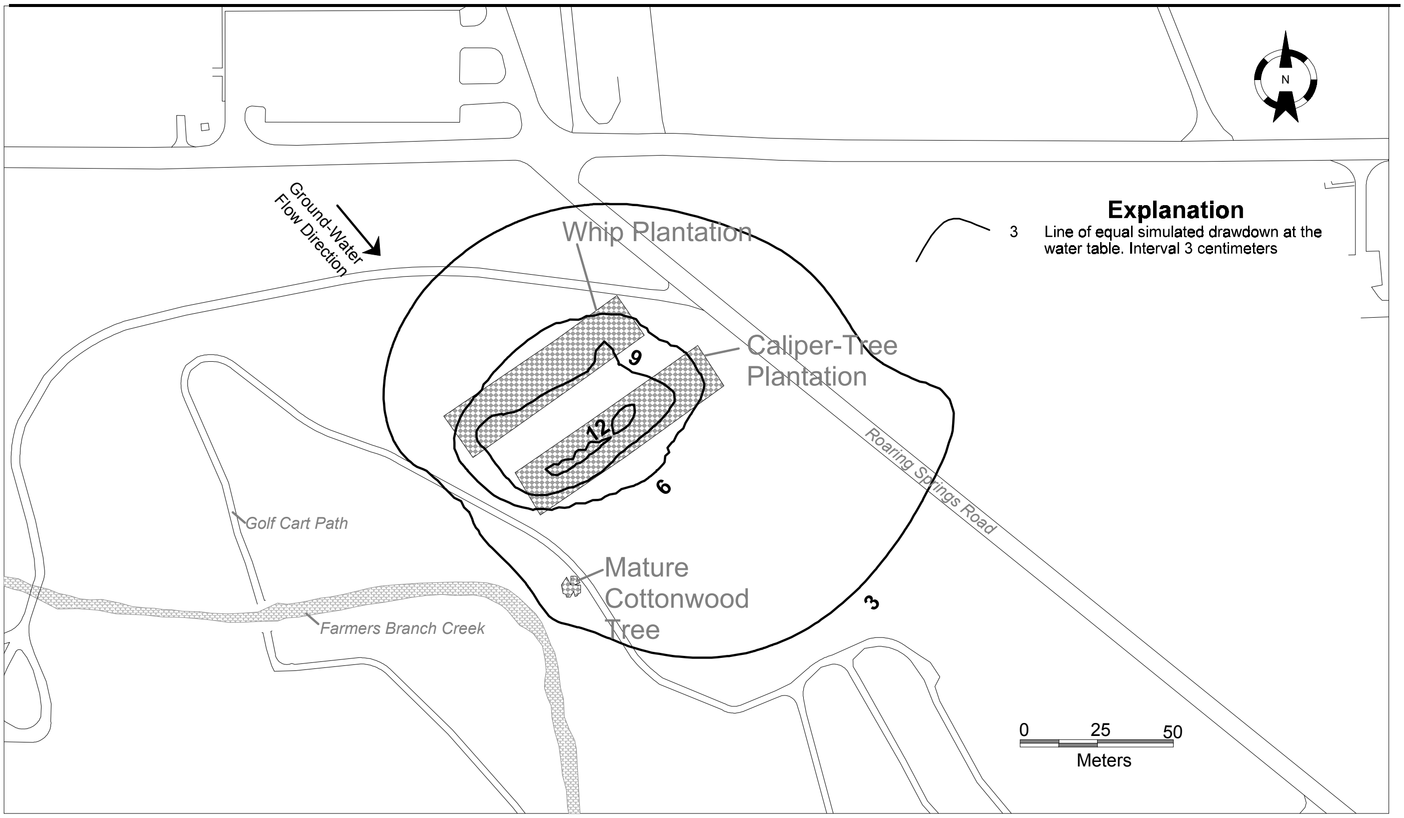


Figure 4-11. Minimum predicted drawdown at the water table for closed-canopy conditions (year 12 and beyond).

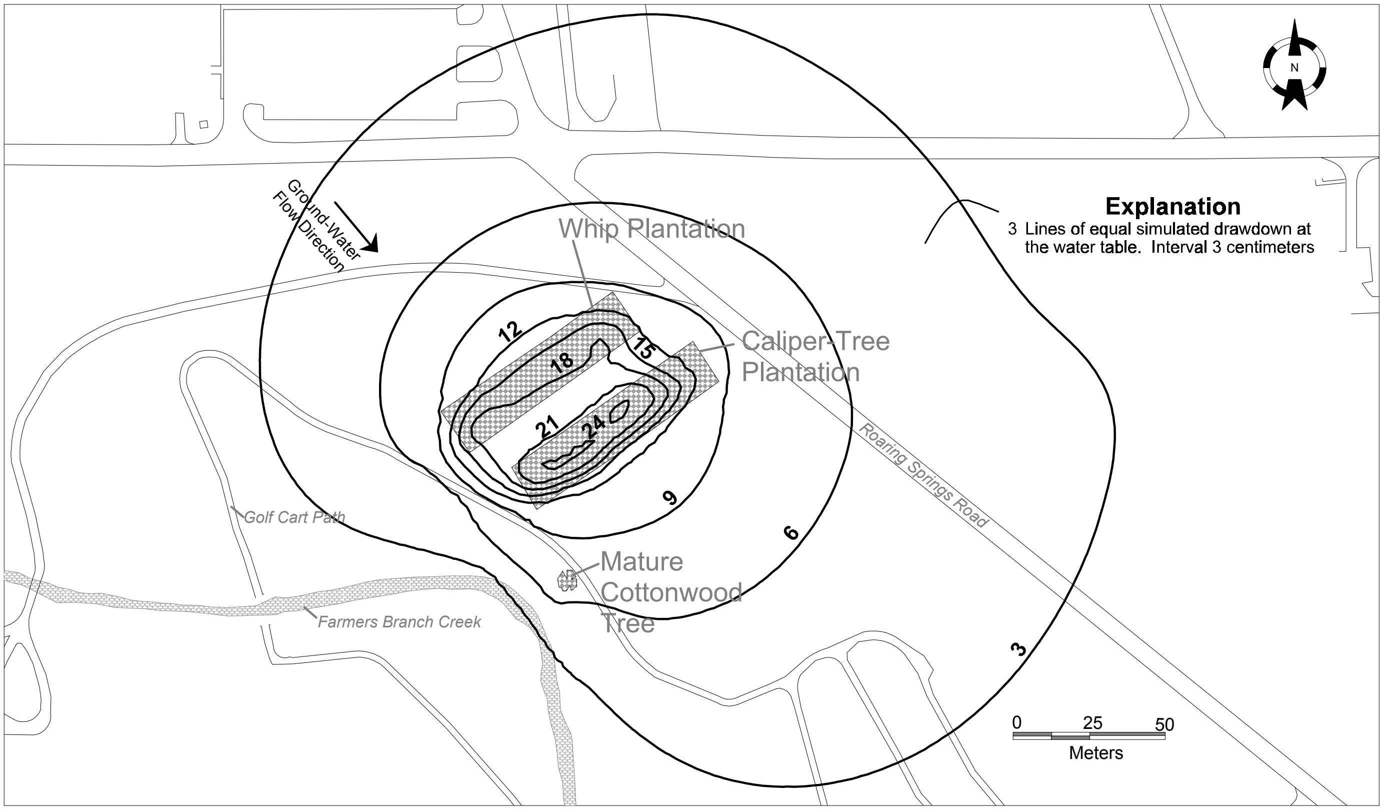


Figure 4-12. Maximum predicted drawdown at the water table for closed-canopy conditions (year 12 and beyond).

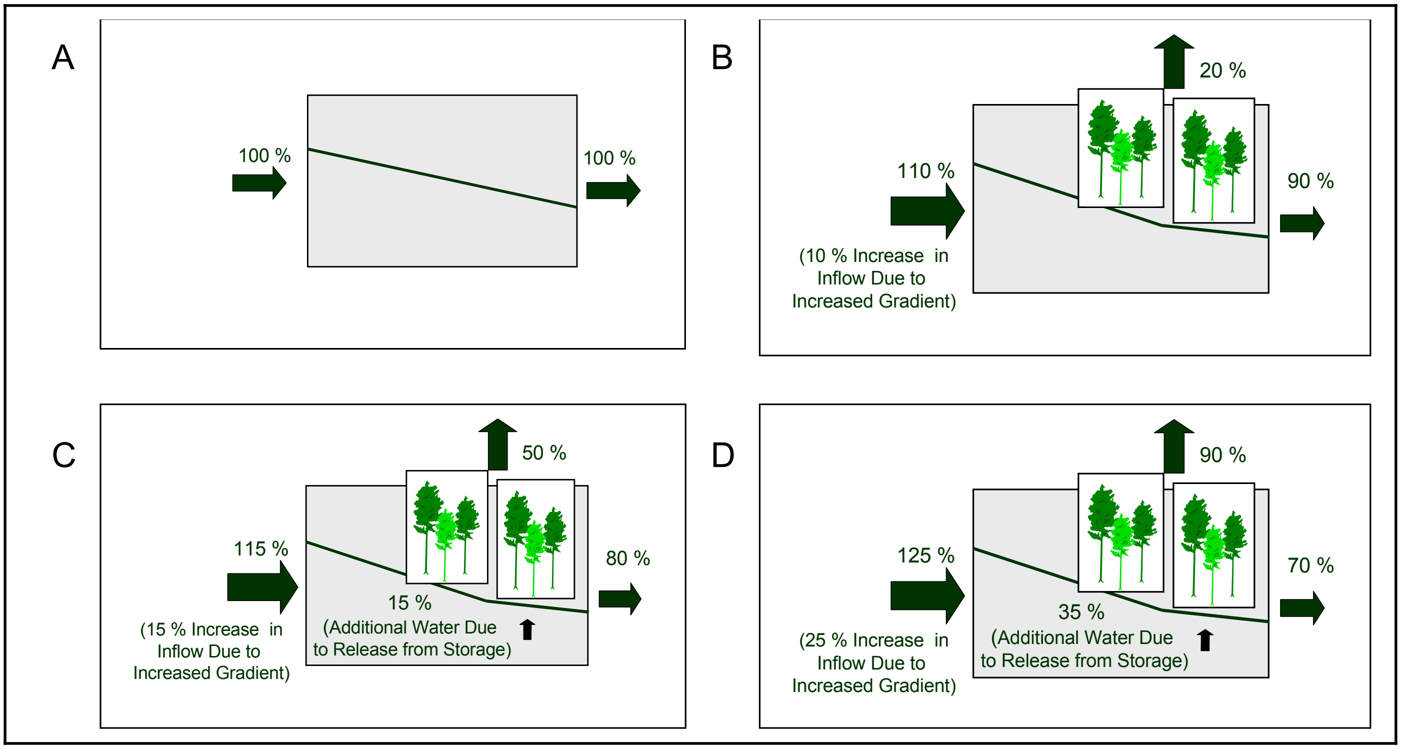


Figure 4-13. Simulated groundwater budget (A) prior to treatment, (B) peak of the third growing season (1998), (C) peak of the growing season once closed canopy has been achieved (year 12 and beyond)–minimum predicted transpiration, and (D) peak of the growing season once closed canopy has been achieved (year 12 and beyond)–maximum predicted transpiration.

tissues, (2) whether there were changes in the concentration of such compounds in the plant tissues over time, and (3) whether there were differences between the samples collected from the plantations and those collected from the mature tree. The results of these analyses were used to determine whether chlorinated ethenes are translocated from the subsurface into the trees at the demonstration site.

Table 4-2 is a summary of the plant tissue data. The table depicts (for each sampling event) plant tissue, tree type, the average concentration of detected volatile compounds, and the number of tissue samples exhibiting detectable levels of that compound. Thirty volatile compounds were scanned as part of the method. However, only seven compounds were detected in the tissue samples. The detected compounds include trichloroethene, cis-1,2 dichloroethene, methylene chloride, tetrachloroethene, chloroform, toluene, and acrolein. Five of the seven volatile compounds detected are chlorinated. Toluene is an aromatic compound and acrolein is an aldehyde.

The following conclusions can be drawn from this data:

1. Chlorinated compounds were commonly encountered in tissue samples during all sampling events. The stem samples generally exhibited the greatest diversity and concentration of chlorinated compounds.
2. With regards to the chlorinated ethenes in the plantations, there was a general increase over time in the percentage of trees that contained the compounds, as well as an increase in the average concentration. The highest concentrations of chlorinated ethenes were encountered during the October 1998 sampling event. All five whip and five caliper-tree samples contained detectable levels of trichhloroethene in the stems. Average stem concentrations were 32.8 µg/kg for the whips and 24.6 µg/kg for the caliper trees.
3. There were no major differences between the whips and caliper-tree plantations with respect to the presence and concentration of VOCs.
4. The concentrations of chlorinated ethenes in the plantations was higher than detected in the mature tree.

The presence and increasing abundance over time of chlorinated ethenes in the plant tissues are an indication that the plantations progressively translocated more contaminants from the subsurface over time. This data cannot be used to assess the fate of these contaminants within the plant tissues or to determine if they are volatilized into the atmosphere.

Tree cores were collected by USGS with an increment borer from 23 mature trees surrounding the demonstration site and analyzed for the presence of TCE and cis-1,2-DCE. Eleven species of trees were sampled,

Table 4-2. Average concentration of detectable volatile compounds in plant tissue [concentrations are in units of µg/kg; ND, non detected; NS, not sampled].

Event	Analyte	Whips			Caliper Trees			Mature Cottonwood		
		Leaf	*Stem*	*Root*	*Leaf*	*Stem*	*Root*	*Leaf*	*Stem*	*Root*
October 1996	Trichloroethene	ND	26 (1)	ND	ND	ND	ND	NS	ND	NS
	Acrolein	ND	15.2 (3)	21.7 (3)	ND	7.0 (2)	9.1 (2)	NS	ND	NS
	Chloroform	ND	3.9 (1)	ND	ND	4.1 (1)	ND	NS	ND	NS
	Methylene Chloride	ND	15 (2)	29 (3)	ND	10 (1)	ND	NS	2.2	NS
	cis-1,2 Dichloroethene	ND	ND	ND	ND	ND	ND	NS	1.2	NS
July 1997	Trichloroethene	ND	ND	NS	ND	ND	NS	ND	ND	NS
	Acrolein	58.8 (5)	136 (3)	NS	19 (1)	46.2 (5)	NS	49	35	NS
	Chloroform	ND	ND	NS	0.73 (1)	ND	NS	120	ND	NS
	Methylene Chloride	151 (5)	153 (3)	NS	168 (5)	ND	NS	ND	ND	NS
	Toluene	0.73 (2)	ND	NS	ND	ND	NS	0.7	ND	NS
	Tetrachloroethene	ND	ND	NS	ND	71 (3)	NS	ND	ND	NS
October 1997	Trichloroethene	1.6 (2)	10.1 (3)	NS	10.4 (3)	9.6 (3)	NS	ND	6.4	NS
	Acrolein	ND	20 (1)	NS	ND	12.5 (4)	NS	ND	ND	NS
	Methylene Chloride	8.3 (3)	6.6 (2)	NS	ND	3.6 (5)	NS	6.3	2.8	NS
	cis-1,2 Dichloroethene	ND	1.9 (3)	NS	ND	1.6 (3)	NS	ND	10	NS
	Toluene	ND	2.3 (3)	NS	4.3 (2)	1.5 (1)	NS	ND	ND	NS
	Tetrachloroethene	ND	ND	NS	ND	5.1 (2)	NS	ND	ND	NS
June 1998	Trichloroethene	ND	44 (1)	140	4.5 (2)	71 (1)	13	ND	13	NS
	Acrolein	ND	ND	25	ND	ND	ND	ND	ND	NS
	cis-1,2 Dichloroethene	ND	14 (1)	ND	ND	15.7 (3)		ND	ND	NS
	Toluene	1.4 (5)	2.3 (2)	1.1	1.1 (2)	2.0 (1)	0.91	ND	0.9	NS
Oct. 1998	Trichloroethene	ND	32.8 (5)	NS	ND	24.6 (5)	NS	ND	2.2	NS
	Acrolein	ND	14.4 (3)	NS	ND	ND	NS	ND	ND	NS
	cis-1,2 Dichloroethene	ND	13.5 (5)	NS	ND	8.9 (4)	NS	ND	2.8	NS

Number in parentheses represents the number of trees for which analyte was detected.
Five whips and five caliper trees were sampled (except roots).

including five cottonwoods, six oaks, two live oaks, two cedars, two willows, one hackberry, one mesquite, one pecan, one American elm, one unidentified elm, and one unidentified species. Cores were collected from a height of approximately 1.5 m above the ground surface.

Most of the trees that were sampled contained TCE and cis-1,2-DCE. A comparison of the results for two trees of different species (willow and cottonwood) that grow immediately adjacent to each other with intertwining roots showed similar TCE concentrations but different cis-1,2-DCE concentrations. These data suggest that concentration differences may be partly a result of tree-species differences. As a result, it is practical to examine the data by comparing concentrations within individual species. Generally, TCE concentrations found within individual species decreased in the directions of decreasing groundwater TCE concentrations. Although most trees contained more TCE than cis-1,2-DCE, in areas where the depth to groundwater was about one meter or less, willow, cottonwood, and American elm trees contained substantially more cis-1,2-DCE than TCE. The data suggest the possibility that these trees promote *in situ* TCE dechlorination in areas where the depth to groundwater is shallow. They also suggest that tree-core data can be useful in locating areas of active dechlorination. More cis-1,2-DCE than TCE also was found in the only two cedars and the only pine that were tested. These trees were in areas where the groundwater TCE concentrations were greater than the groundwater cis-1,2-DCE concentrations, suggesting that either the trees take up cis-1,2-DCE more efficiently than TCE or dechlorination of TCE occurs within the trees. The depth to groundwater at these trees was up to 8 meters. No TCE was found in trees that grow in areas that contain no TCE in the groundwater. Additional information on the concentration TCE and 1,2-DCE measured in trees within the study area is contained in the report entitled "Trichloroethene and cis-1,2-dichloroethene concentrations in tree trunks at the Carswell Golf Course, Fort Worth, Texas (Vroblesky, 1998)

A research team led by USEPA (Athens, GA) investigated the kinetics of transformation of TCE for leaf samples collected from seven trees (cedar, hackberry, oak, willow, mesquite, cottonwood whip, cottonwood caliper tree). Each of the plant species investigated appears to have properties that are effective in degrading TCE. Specifically, all leaf samples showed dehalogenase activity. Pseudo first-order rate constants were determined for the samples. The average and standard deviation for all seven rate constants is 0.049 +-0.02 hr^{-1} (Table4-3). This corresponds to a half-life of 14.1 hours. These kinetics are fast relative to other environmental transport and transformation processes with the exception of volatilization for TCE. As a result, it is unlikely that degradation within the trees will be the rate limiting step in a Phytoremediation system. Additional information on evidence of dehalogenase activity in tree tissue samples is contained in a report entitled "Dehalogenase and nitroreductase activity in selected tree samples: Carswell Air Force Base" (Wolfe et al., 1999)

Evaluate geochemical indices of subsurface oxidation-reduction processes

It was hypothesized that the Phytoremediation system would promote the biodegradation of TCE in the contaminated aquifer by transforming conditions in the aquifer from aerobic to anaerobic. Specifically, it was thought that the planted system would introduce relatively high concentrations of biologically available organic carbon through the decomposition of root material and the production of root exudates that would serve as the primary substrate for microorganism growth and subsequent depletion of dissolved oxygen. Then, the anaerobic microbial utilization of this natural carbon source would drive reductive decholorination of the dissolved TCE in the aquifer (Wiedemeier and others, 1996). The dechlorination pathway for TCE is trichloroethene -> cis-1,2-dichloroethene + Cl -> vinyl chloride + 2Cl -> ethene +3Cl. The efficiency of TCE degradation varies depending on microbially mediated redox reactions (most efficient to least efficient - methanogenesis, sulfate reduction, iron (III) reduction, and oxidation). Thus, an accurate determination of redox conditions in the aquifer could be used to evaluate the potential for reductive dechlorination.

Determination of redox conditions or the terminal electron-accepting process (TEAP) in an aquifer can be accomplished by several on-site measurements of groundwater chemistry. Detection and measurement of methane indicates that methanogenesis is occurring near the well sampled. Measurement of the redox pairs Fe2+/Fe3+ and SO42-/S2- using standard methods usually distinguishes between iron (III)-reduction and sulfate-reduction processes. If appreciable dissolved oxygen (DO) (more than 2 milligrams per liter (mg/L)) is present in the groundwater, reductive dechlorination is an unlikely process. As these lines of evidence sometimes conflict, the measurement of molecular hydrogen (H_2), which is produced as an intermediate product of anaerobic microbial metabolism, can be an effective method to elucidate the predominant TEAP (Chapelle, 1993).

Data were collected to determine the concentrations and distribution of contaminants, daughter products, and indices of redox conditions in the aquifer. Specifically, TCE and cis-1,2-DCE concentrations were monitored, as were total organic carbon content, methane production, sulfide concentrations, ferrous and ferric iron ratios, dissolved oxygen concentrations, and hydrogen gas generation. Samples were collected from monitoring locations upgradient of the plantations, within the plantations, and downgradient of the plantations. In addition, samples were taken from a monitoring point immediately adjacent to the mature cottonwood tree to provide insight into conditions in the aquifer once the planted trees have matured. Groundwater sampling locations are depicted in Figure 4-1. (A lesson learned from this data-collection effort is that metal on groundwater-level floats and other downhole instrumentation can interfere with hydrogen gas measurements.)

Table 4-4 summarizes the results of the VOC analyses based on the average concentration within each of the areas of the site (upgradient, plantations, downgradient, mature tree) for each event. An examination of the summarized contaminant data indicates that there was a general decrease in the concentration of TCE throughout the demonstration site over the course of the study. This decrease, however, does not appear to be predominantly related to the establishment of the whip and caliper-tree plantations. This is because a decrease in TCE concentration was observed in the upgradient monitoring wells as well as in the wells within the plantations. In addition, the downgradient monitoring wells did not exhibit a significant decrease in TCE concentration. The change in TCE concentration within the study area over time may be attributed to dilution from recharge to the aquifer and volatilization of TCE from the water table.

The data also indicate that the TCE concentration in the aquifer beneath the mature cottonwood tree was significantly lower than elsewhere at the demonstration site. In addition, DCE concentrations were much higher beneath the mature tree than upgradient, within, or downgradient of the planted trees.

Table 4-5 summarizes the ratio of TCE to cis-1,2-DCE for each area that was sampled (upgradient, plantations, downgradient, mature tree). The ratio of TCE to cis-1,2-DCE can reveal subtle changes in the aquifer due to biodegradation of TCE to its daughter product cis-1,2-DCE that may be difficult to detect from concentration data alone.

The TCE to cis-1,2-DCE ratio in upgradient, plantation, and downgradient wells indicate that there was a general

Table 4-3. Pseudo first-order disappearance rate constants for the plant-leaf mediated transformation of TCE.

Tree	TCE, hr^{-1}
Cedar	0.052
Hackberry	0.078
Oak	0.067
Willow	0.015
Mesquite	0.059
Cottonwood (whip)	0.044
Cottonwood (caliper)	0.027

Table 4-4. Average TCE and DCE concentration in monitoring wells.

	TCE ug/L				Cis-1,2-DCE ug/L				Trans-1,2-DCE ug/L			
Event	Up Gradient[a]	Plantations[b]	Down Gradient[c]	Mature Tree[d]	Up Gradient	Plantations	Down Gradient	Mature Tree	Up Gradient	Plantations	Down Gradient	Mature Tree
Dec-96	818	710	512	89	176	121	101	160	1.2	2.4	2.0	8.8
May-97	771	548	523	38	174	114	109	230	3.6	1.1	1.3	11.5
Jul-97	709	581	571	31	179	157	143	240	3.6	3.0	3.3	12.8
Jul-98	480	486	478	157	118	109	98	150	1.8	2.3	2.0	12.5
Sep-98	490	420	484	135	158	172	145	217	7.7	4.5	4.6	18.3

(a) Upgradient monitoring points consist of wells 501, 502, 503, 513, and 518

(b) Plantation monitoring points consist of wells 504, 505, 507, 508, 509, 514, 515, 524, and 525

(c) Downgradient monitoring points consist of wells 526, 527, 528, and 529

(d) Mature tree monitoring points consist of wells 510, 511, and 512

Table 4-5. TCE to cis-1,2-DCE ratio.

TCE/cis-1,2-DCE				
Event	Up Gradient	Plantations	Down Gradient	Mature Tree
Dec-96	4.64	5.88	5.08	0.56
May-97	4.43	4.79	4.80	0.16
Jul-97	3.96	3.71	3.99	0.13
Jul-98	4.09	4.45	4.88	1.05
Sep-98	3.11	2.44	3.34	0.62

decrease in the ratio over time throughout the demonstration site. Again, the change in the ratio generally cannot be attributed to the planted trees because the change was detected in the upgradient wells. An exception to this pattern was observed in September 1998. The TCE to cis-1,2-DCE ratio in the plantation wells at this time was 2.44, which is notably less than what was measured in wells upgradient and downgradient of the planted area. These data may indicate that reductive dechlorination processes were beginning to become established beneath the plantations by the end of the third growing season.

The data in Table 4-5 also indicate that significant reductive dechlorination was occurring in the vicinity of the mature cottonwood tree during the demonstration period. The ratio of TCE to cis-1,2-DCE was generally an order of magnitude less than elsewhere at the demonstration site. As will be subsequently discussed, geochemical conditions beneath the mature cottonwood tree appear to have been transformed from aerobic to anaerobic conditions that support reductive dechlorination.

An investigation to determine whether the planted trees were capable of promoting a shift in the aquifer from aerobic to anaerobic conditions during the three-year demonstration period was conducted by the USGS. The results are summarized in Table 4-6. The study concluded that the overall groundwater geochemistry beneath the plantations was beginning to change in response to the planted trees by the peak of the third growing season. Dissolved oxygen concentrations had decreased and total iron concentrations had increased at the southern end of the whip plantation by this time. This is in agreement with the observed changes in the ratio of TCE to cis-1,2-DCE and indicates that reducing conditions were beginning to support the biodegradation of TCE beneath this end of the whip plantation. It was also concluded that reducing conditions were present in the aquifer in the vicinity of the mature cottonwood tree as indicated by low dissolved oxygen and high total iron concentrations, as well as the detection of hydrogen and methane gases. Additional information on this subject is contained in a report entitled "Phreatophyte influence on reductive dechlorination in a shallow aquifer contaminated with trichloroethene (TCE)" (Lee et al., 2000).

Evaluate microbial contributions to reductive dechlorination

To assess the mechanisms and rates of biodegradation in an aquifer, it is best to look at the spatial distribution of the different microbial populations on the sediment and in the pore water in addition to the concentrations and distribution of redox reactants and products in the groundwater. As a result, a reconnaissance study of microbial activity in soil and groundwater beneath the whip plantation, the caliper-tree plantation, and the mature cottonwood tree near the site was conducted by the USGS in February and June of 1998. The purpose of the study was to determine the nature of the microbial community at the demonstration site and to determine if the microbial community had evolved into one that would support the reductive dechlorination of TCE and its daughter products. The presence of large populations of sulfate-reducing bacteria and methanogenic bacteria are indicative of environments that are favorable for reductive dechlorination.

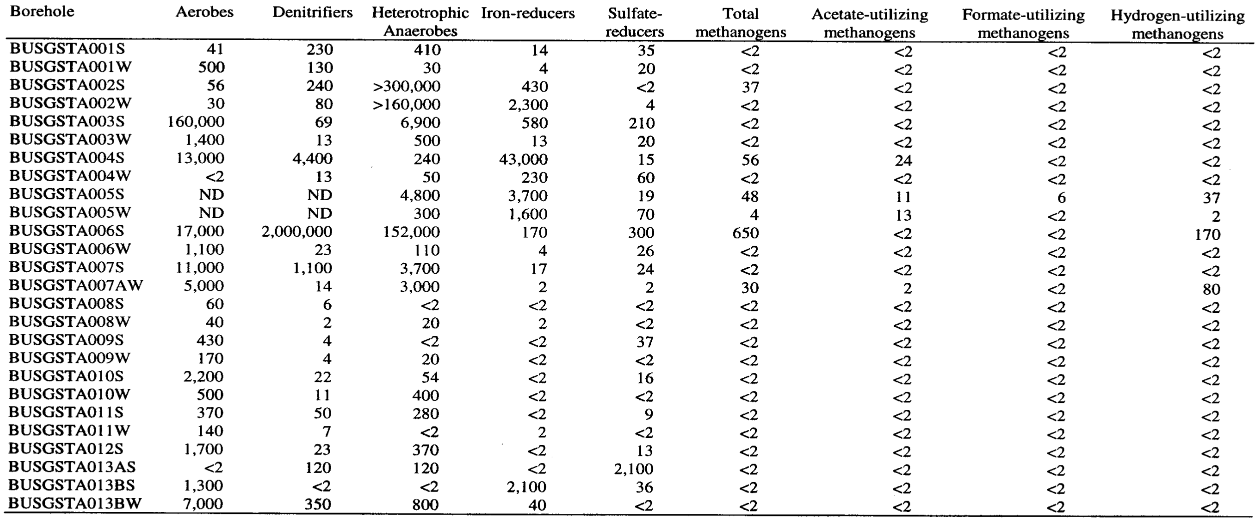
Results of the study are summarized in Table 4-7. Specifically, Table 4-7 includes the Most Probable Number (MPN) values for physiologic microbial types in soil samples (S) and groundwater samples (W) throughout the

Table 4-6. Selected chemical data from wells used to define terminal electron accepting processes (TEAP) at the demonstration site [mg/L, milligrams per liter; <, less than; nM, nanomolar per liter; µM, micromoles per liter; TEAP, terminal electron accepting process; E, estimated.

Area	Well No.	Dissolved Oxygen (mg/L)				Dissolved Sulfide (mg/L)				Total Dissolved Iron (mg/L)			
		1997		1998		1997		1998		1997		1998	
		July	Nov.	Feb.	June	July	Nov.	Feb.	June	July	Nov.	Feb.	June
Upgradient	501	3.5	3.0	3.0	4.7	<0.001	<0.001	<0.001	<0.001	0.1	<0.1	<0.1	<0.1
Mature tree	511	1.1	0.7	0.9	0.8	<0.001	0.005	0.007	<0.001	4.9	7.7	3.9	5.5
Whip Plantings	514	2.5	1.2	0.7	1.7	<0.001	0.120	0.056	<0.001	<0.1	<0.1	0.1	0.2
Caliper Plantings	515	3.0	2.5	1.5	2.9	<0.001	<0.001	<0.001	<0.001	0.1	<0.1	0.1	<0.1
Between Planted Trees	523	3.5	3.5	3.0	4.5	<0.001	<0.001	<0.001	<0.001	<0.1	<0.1	<0.1	<0.1
Down-gradient	529	3.5	4.0	3.0	2.7	<0.001	<0.001	<0.001	<0.001	<0.1	<0.1	<0.1	<0.1

Area	Well No.	Molecular Hydrogen (nM)				Methane (µM)				TEAP
		1997		1998		1997		1998		
		July	Nov.	Feb.	June	July	Nov.	Feb.	June	
Upgradient	501	<0.05	<0.05	<0.05	0.3	<0.1	<0.1	<0.1	<0.1	Reduction of dissolved oxygen
Mature tree	511	<0.05	<0.05	0.1E	0.9E	5.1	7.5	24	15	Methanogenesis
Whip Plantings	514	<0.05	12.2	0.7	0.5	<0.1	<0.1	<0.1	<0.1	Iron (III) reduction
Caliper Plantings	515	<0.05	0.8	<0.05	0.1	<0.1	<0.1	<0.1	<0.1	Reduction of dissolved oxygen
Between Planted Trees	523	0.47	<0.05	<0.05	0.23	<0.1	<0.1	<0.1	<0.1	Reduction of dissolved oxygen
Down-gradient	529	<0.05	<0.05	<0.05	0.5	<0.1	<0.1	<0.1	<0.1	Reduction of dissolved oxygen

Table 4-7. Results of microbial population survey ["S" denotes soil sample, "W" denotes water sample]



Borehole	Aerobes	Denitrifiers	Heterotrophic Anaerobes	Iron-reducers	Sulfate-reducers	Total methanogens	Acetate-utilizing methanogens	Formate-utilizing methanogens	Hydrogen-utilizing methanogens
BUSGSTA001S	41	230	410	14	35	<2	<2	<2	<2
BUSGSTA001W	500	130	30	4	20	<2	<2	<2	<2
BUSGSTA002S	56	240	>300,000	430	<2	37	<2	<2	<2
BUSGSTA002W	30	80	>160,000	2,300	4	<2	<2	<2	<2
BUSGSTA003S	160,000	69	6,900	580	210	<2	<2	<2	<2
BUSGSTA003W	1,400	13	500	13	20	<2	<2	<2	<2
BUSGSTA004S	13,000	4,400	240	43,000	15	56	24	<2	<2
BUSGSTA004W	<2	13	50	230	60	<2	<2	<2	<2
BUSGSTA005S	ND	ND	4,800	3,700	19	48	11	6	37
BUSGSTA005W	ND	ND	300	1,600	70	4	13	<2	2
BUSGSTA006S	17,000	2,000,000	152,000	170	300	650	<2	<2	170
BUSGSTA006W	1,100	23	110	4	26	<2	<2	<2	<2
BUSGSTA007S	11,000	1,100	3,700	17	24	<2	<2	<2	<2
BUSGSTA007AW	5,000	14	3,000	2	2	30	2	<2	80
BUSGSTA008S	60	6	<2	<2	<2	<2	<2	<2	<2
BUSGSTA008W	40	2	20	2	<2	<2	<2	<2	<2
BUSGSTA009S	430	4	<2	<2	37	<2	<2	<2	<2
BUSGSTA009W	170	4	20	<2	<2	<2	<2	<2	<2
BUSGSTA010S	2,200	22	54	<2	16	<2	<2	<2	<2
BUSGSTA010W	500	11	400	<2	<2	<2	<2	<2	<2
BUSGSTA011S	370	50	280	<2	9	<2	<2	<2	<2
BUSGSTA011W	140	7	<2	2	<2	<2	<2	<2	<2
BUSGSTA012S	1,700	23	370	<2	13	<2	<2	<2	<2
BUSGSTA013AS	<2	120	120	<2	2,100	<2	<2	<2	<2
BUSGSTA013BS	1,300	<2	<2	2,100	36	<2	<2	<2	<2
BUSGSTA013BW	7,000	350	800	40	<2	<2	<2	<2	<2

BUGSTA001	Upgradient from trees in open space	BUGGSTA009	Within whips, south side
BUGGSTA002	Within whips, south side	BUGGSTA010	Within whips, north side
BUGGSTA003	Within caliper-trees, south side	BUGGSTA011	Within caliper-trees, north side
BUGGSTA004	Downgradient from trees in open space	BUGGSTA012	In field behind house at 328 Tinker Dr.
BUGGSTA005	Low spot west of mature cottonwood	BUGGSTA013A	Under mature cottonwood in front of house at 328 Tinker Dr., unsaturated zone
BUGGSTA006	Under mature cottonwood near site	BUGGSTA013B	Under mature cottonwood in front of house at 328 Tinker Dr., saturated zone
USGSTA007	Under mature cottonwood near site		
BUGGSTA007A	Under mature cottonwood near site		
BUGGSTA008	Within caliper-trees, south side		

study area. Microbial populations within the area of the tree plantations (BUSGSTA002, 003, 008, 009, 010, and 011) were similar to the background sites (BUSGSTA001 and 012) with the exception of locally increased numbers of anaerobic microorganisms and the presence of methanogenic microorganisms. These data suggest that the microbial community appeared to be moving towards an assemblage capable of supporting reductive dechlorination by the third growing season. The microbial population in the area of the mature cottonwood tree near the site (BUGSTA006 and 007) included a vigorous community that supported both hydrogen-oxidizing and acetate-fermenting methanogens. This active anaerobic population is assumed to be responsible for the decrease in TCE concentration and the generation of daughter products beneath the mature cottonwood tree. A sediment sample from beneath the mature tree contained identifiable acidic compounds, including phenol, benzoic acid, and acetic acid, which are common intermediates observed in anaerobic ecosystems where complex organics are undergoing biodegradation and are consistent with the complex organic root exudates at this location. These compounds are most likely acting as electron donors for the reductive dechlorination of the TCE beneath the mature cottonwood tree. The microbial population downgradient of the plantations (BUGSTA004) contained an anaerobic community structure similar to populations present beneath the plantations. Additional information on the subject of microbial dechlorination in the study area can be found in the report entitled "The role of microbial reductive dechlorination of TCE at the phytoremediation site at the Naval Air Station, Fort Worth, Texas" (Godsy et al., 2000).

Although the microbial data suggests that the Plant system may be capable of modifying the subsurface microbial community in the aquifer beneath the planted trees to one that can begin supporting reductive dechlorination of TCE, TCE degradation rates cannot be determined from the data. In order to determine the degradation rate of TCE in subsurface sediments at the demonstration site, laboratory microcosms were established using sediment and water samples collected from locations in and near the site. Preliminary results indicate that TCE was converted to cis-1,2-DCE in a microcosm created from sediment taken from beneath the mature cottonwood tree and water collected from beneath the caliper trees. The first order kinetic rate of TCE disappearance in this microcosm was 0.34 day^{-1} (Ean Warren, USGS, written commun., 2000). Further microcosm experiments are planned.

4.5 Discussion

The SRWCGT system at the Carswell Golf Course is a low-cost, easy to implement, low-maintenance system that is consistent with a long-term contaminant reduction strategy. The system produces virtually no process residuals and requires minimal maintenance. Maintenance requirements include occasional pruning and irrigation. The system is an "evolving" process that increases its effectiveness over time. The following discussion summarizes the predicted effectiveness of the system as configured at the Carswell Golf Course site and presents recommendations for implementing a similar system at other sites.

The SRWCGT system is useful for intercepting and remediating a chlorinated ethene contaminant plume. The technology uses two mechanisms to achieve this goal; hydraulic influence and in-situ biologically mediated reductive dechlorination. Hydraulic influence involves the interception and usage of contaminated groundwater by the trees. Biologically-mediated reductive dechlorination involves the generation of subsurface biodegradable organic matter by the tree root systems, which drives the microbial communities in the underlying aquifer from aerobic to anaerobic ones that are capable of supporting reductive dechlorination of TCE.

With respect to hydraulic influence, the trees in both the whip and caliper-tree plantations at the demonstration site began to use water from the aquifer and reduced the volume of contaminated groundwater leaving the site during the three-year demonstration. The maximum reduction in the outflow of contaminated groundwater that could be attributed to the trees was approximately 12 percent and was observed at the peak of the third growing season. The reduction in the mass flux of TCE across the downgradient end of the treatment system at this time was closer to 11 percent because TCE concentrations were slightly higher during the third growing season than at baseline. The maximum observed drawdown of the water table occurred near the center of the treatment system at this time and was approximately 10 centimeters. A groundwater flow model (MODFLOW) of the demonstration site indicates that the volume of water that was transpired from the aquifer during the peak of the third growing season was probably closer to 20 percent of the initial volume of water that flowed through the site because there was an increase in groundwater inflow to the site due to an increase in the hydraulic gradient on the upgradient side of the drawdown cone.

Tree-growth and root-growth data collected from the demonstration site are consistent with the observations of hydraulic influence of the trees on the contaminated aquifer. Trees in the whip plantation, which were planted approximately 1.25 meters apart, were starting to approach canopy closure by the end of the third growing season. This observation indicates that the trees were transpiring a significant amount of water at this time. (A plantation approaches its maximum transpiration potential once it achieves a closed canopy because a closed canopy limits leaf area.) The caliper trees were planted 2.5 meters apart and although the plantation was not as close to achieving a closed canopy, individual caliper trees transpired just over twice the water that individual whips transpired. As a result, the volume of water that was transpired by the two plantations was similar because there were half as many caliper trees as whips. Tree roots in both plantations had reached the water table (275 cm for the whips and 225 cm for the caliper trees) by the second growing season.

There were no data collected during the demonstration that favored the planting of caliper trees over the less expensive whips. The physiologically-based model PROSPER, which was used to predict out-year transpiration rates at the demonstration site, indicates that the whip and caliper-tree plantations will eventually transpire a similar amount of water - 25 to 48 centimeters per growing season depending on climatic conditions, soil moisture, and root growth. Forty-eight to fifty-eight percent of this predicted evapotranspiration is expected to be derived from the contaminated aquifer (saturated zone) regardless of the planting strategy. In general, the closer trees are planted, the sooner a plantation may achieve closed canopy. However, it is important to consider the increased chance for disease when trees are closely spaced. There is a body of literature on short rotation wood culture that can be used to guide decisions with regard to tree spacing in a SRWCGT system (see Appendix B, Vendor's Section 5.0).

Since the SRWCGT system had not achieved maximum hydraulic control during the period of demonstration, a modeling approach was used to make predictions with regards to out-year hydraulic control. The groundwater flow model indicates that once the tree plantations have achieved a closed canopy, the reduction in the volumetric flux of contaminated groundwater across the downgradient end of the site will likely be between 20 and 30 percent of the initial amount of water that flowed through the site. The actual amount of water that will be transpired from the aquifer by the tree plantations will be closer to 50 to 90 percent of the volume of water that initially flowed through the site. The discrepancy between the reduction in the volumetric outflow of groundwater and the volume of water transpired from the aquifer can be attributed to the predicted increase in groundwater inflow to the site and the release of water from storage in the aquifer. No hydraulic control was observed during the dormant season from November to March and no hydraulic control is predicted for future dormant seasons.

In general, the amount of hydraulic control that can be achieved by a Tree system is a function of site-specific aquifer conditions. A planted system can be expected to have a greater hydrologic affect on an aquifer at a site that has an initially low volumetric flux of groundwater as opposed to a site where the flux of contaminated groundwater is significantly greater. The parameters of hydraulic conductivity, hydraulic gradient, saturated thickness, and aquifer width in the treatment zone all contribute to the volumetric flux of groundwater through a site. The horizontal hydraulic conductivity at the demonstration site in Fort Worth, Texas is approximately 6 meters/day. The natural hydraulic gradient is close to two percent and the saturated thickness of the aquifer is between 0.5 and 1.5 meters. Volume of water in storage in an aquifer will also affect system performance. Although the current study did not investigate the effect of aquifer depth; it is possible that a greater percent of total evapotranspiration could be derived from an aquifer with a shallower water table.

When designing for hydraulic control at a Phytoremediation system, it is important to keep the remediation goals in mind. In other words, it may not be desirable to achieve full hydraulic control at a site if full control would adversely affect the groundwater / surface water system downgradient of the site. At the demonstration site in Texas, the receptor is Farmers Branch Creek, which has very low flow (less than 1 cubic foot per second) during the summer months (peak transpiration). The optimal performance at such a site may be to keep the plume from discharging into the creek without drying up the creek, particularly since hydraulic control is only one mechanism that contributes to the cleanup of a groundwater plume by Phytoremediation System. A groundwater flow model of a potential site is ideal for addressing such design concerns.

With respect to the fate of the contaminants that were taken up into the planted trees, TCE and its daughter products were commonly detected in tissue samples of roots, stems and leaves. Generally, there was an increase over time in the percentage of planted trees in which the compounds were detected. Stem tissue generally exhibited the greatest diversity and concentration of chlorinated compounds. It was concluded that the planted cottonwood trees have properties that are effective in degrading TCE. Specifically, the leaf samples showed dehalogenase activity. An investigation into the kinetics of transformation of TCE for leaf samples concluded that it is unlikely that degradation within the trees will be the rate-limiting step in a Phytoremediation system. As a result, it may be better to use species that are native to a proposed area rather than to use genetically altered plants that are designed to enhance metabolism of TCE.

With respect to biologically-induced reductive dechlorination, there is evidence that the aquifer beneath the planted trees was beginning to support anaerobic microbial communities capable of biodegradation of TCE within three years of planting. Specifically, microbial data from soil and groundwater samples indicate that the microbial community beneath the planted trees had begun to move towards an assemblage capable of supporting reductive dechlorination during the demonstration period. In addition, dissolved oxygen concentrations had decreased and total iron concentrations had increased at the southern end of the whip plantation where the water table is closest to land surface. The ratio of TCE to cis-1,2-DCE had also decreased at this location beneath the whip plantation, which suggests that the shift toward anaerobic conditions in this part of the aquifer was beginning to support the biodegradation of TCE. Significant contaminant reduction by this mechanism, however, had not occurred across the demonstration site by the end of the demonstration period.

Data from the aquifer beneath the mature cottonwood tree near the planted site support the conclusion that reductive dechlorination can occur beneath cottonwood trees with established root systems. The ratio of TCE to cis-1,2-DCE beneath the mature tree was typically one order of magnitude less than elsewhere at the site during the demonstration. The microbial population in the area of the mature cottonwood tree included a vigorous community that supported both hydrogen oxidizing and acetate fermenting methanogens. This active anaerobic population is assumed to be responsible for the decrease in TCE concentration and the generation of daughter products beneath the mature cottonwood tree.

The data collected during the demonstration are insufficient to conclude when significant reductive dechlorination will occur beneath the planted trees. Data collected during the fifth dormant season after the period of demonstration had ended indicate that the aquifer was generally anaerobic beneath the planted trees while it was aerobic upgradient and downgradient of the trees. It is reported in the literature that hybrid poplar plantations sequester significant quantities of soil carbon due to tree root growth by the time they are six years old. It is likely that this increase in soil organic carbon would be enough to promote reductive dechlorination of dissolved TCE in the underlying aquifer, including during the dormant season. The only conclusive information on the future timing of significant reductive dechlorination in the aquifer, however, can be extrapolated from the mature tree. The mature cottonwood was approximately 20 years old during the demonstration; as a result, the planted site will likely reach this level of contaminant reduction within this time frame.

Even though reductive dechlorination was observed around the mature cottonwood tree, the presence of TCE daughter products, as well as residual TCE, indicate that the reductive dechlorination process has not fully mineralized the contaminants of concern to innocuous compounds. There is no field evidence from this study that suggest complete in-situ biodegradation of TCE and its daughter products can be achieved.

In summary, the first three growing seasons at the Phytoremediation system demonstration site resulted in a reduction in the mass of contaminants moving off site. The maximum observed reduction in the mass flux of TCE across the downgradient end of the demonstration site was 11 percent. An increase in the hydraulic influence of the trees and the reductive dechlorination of TCE in the aquifer is expected as the system matures. A solute transport model would be necessary to determine the relative importance of hydraulic control, reductive dechlorination, and sorption in the out years.

SECTION 5
OTHER TECHNOLOGY REQUIREMENTS

5.1 Environmental Regulation Requirements

State and local regulatory agencies may require permits prior to implementing a phytoremediation technology like the Short Rotation Woody Crop Groundwater Treatment (SRWCGT) system. Most federal permits will be issued by the authorized state agency. Depending upon the characteristics of the site and the nature of a particular application, the state may also require a Treatment, Storage, and Disposal (TSD) Permit for on-site storage of a hazardous waste for greater than 90 days. An air permit issued by the state Air Quality Control Region may be required if air emissions in excess of regulatory criteria, or of toxic concern, are anticipated. Discharge of wastewater is highly unlikely during SRWCGT. However, wastewater discharge permits may be required if any such wastewater were to be discharged to a POTW. If remediation is conducted at a Superfund site, federal agencies, primarily the U.S. EPA, will provide regulatory oversight. If off-site disposal of contaminated waste is required, the waste must be taken to the disposal facility by a licensed transporter.

Section 2 of this report discusses the environmental regulations that may apply to the SRWCGT process.

5.2 Personnel Issues

The number of personnel required to implement the SRWCGT technology is largely dependent on the size of the area to be treated. Large sites, requiring extensive site preparation and assembly of a large irrigation system may require several individuals (inclusive of contractors); especially if there are constraints on time. For smaller sites, requiring minimal site preparation, as few as two people may be needed for the actual treatment technology related activities. After site setup, labor associated with a tree-based phytoremediation system such as the one demonstrated at the Carswell Golf Club is limited generally to monthly or bimonthly ground maintenance tasks and monitoring and sampling events. These tasks could be accomplished by one individual over a one to three day period. Labor associated with monitoring and sampling events could be reduced somewhat through automated data collection using data loggers. Data loggers would enable real-time remote access of information pertaining to tree growth, hydraulic conditions and soil moisture. Monitoring and sampling events will likely involve tree measurements (i.e., tree height, canopy width and tree trunk diameter), additional water level measurements, calibration checks on automated monitoring systems, groundwater sampling, rhizosphere soil sampling and tree tissue sampling

Estimated labor requirements for a hypothetical 200,000 ft^2 site are discussed in detail in Section 3 of this report.

For most sites, the personnel protective equipment (PPE) for workers will include steel-toed shoes or boots, safety glasses, hard hats, and chemical resistant gloves. Depending on contaminant types, additional PPE (such as respirators) may be required. Noise levels would usually not be a concern for an application of a SRWCGT technology. However some equipment used for crop cultivation and vegetative clearing and regrading (i.e. tillers, mowers, chain saws, etc.) could create appreciable noise. Thus, noise levels should be monitored for such equipment to ensure that workers are not exposed to noise levels above the time weighted average of 85 decibels over an 8-hour day. If this level is exceeded and cannot be reduced, workers would be required to wear hearing protection.

5.3 Community Acceptance

Potential hazards to a surrounding community may include exposure to particulate matter that becomes airborne during regrading and tilling operations. Air emissions of VOCs is possible if those contaminants are also present in the soil. Particulate air emissions can be controlled by dust suppression measures.

Overall, there are few environmental disturbances associated with SRWCGT. No appreciable noise, beyond that generated by the short term use of agricultural equipment, is ever anticipated for the majority of the treatment time. A fence may be desirable to keep unauthorized visitors from entering the site.

SECTION 6
TECHNOLOGY STATUS

This section discusses the experience of the developers in performing treatment using the Short Rotation Woody Crop Groundwater Treatment (SRWCGT)System. It also examines the capability of the developers in using the technology at sites with contaminant mixtures.

6.1 Previous Experience

In addition to the demonstration performed on chlorinated VOCs at the Carswell Golf Club site, the Aeronautical Systems Center Engineering Directorate Environmental Safety and Health Division has extensive experience in site investigations and remediations at hundreds of site nationwide involving a variety of metals, fuels, VOCs, and other DoD unique compounds. Currently other field scale site investigations and remediations employing phreatophytic trees in a variety of climates and hydraulic regimes are being conducted. Bench and pilot scale investigations testing the ability of trees to handle other recalcitrant compounds like perchloroethylene, 1,1,1,-trichloroethane, and perchlorate have also been conducted with promising results.

6.2 Scaling Capabilities

The planting approach employed in this demonstration have been used by the pulp and paper industries worldwide at much larger scales than that of the demonstration site. Several documents developed by the Department of Energy's Oak Ridge National Laboratory Biomass/Biofuel Group offer recommendations with regard to the selection, planting, care, and harvesting of various trees and grasses amendable to short rotation energy and fiber crops.

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Appendix A

DATA Used to Evaluate Primary Project Objective

Appendix A

DATA USED TO EVALUATE PRIMARY PROJECT OBJECTIVE (SEE TABLE 4-1)

Hydraulic Gradient Across Downgradient End of Planted Area

	Water Table Altitude - Well 522	Water Table Altitude - Well 529	Distance Between Wells	Gradient[a]
Baseline (November 1996)	179.93 m above sea level	178.96 m above sea level	61 m	0.0159
Peak 2nd Season (1997)	180.13 m above sea level	179.19 m above sea level	61 m	0.0154
Late 2nd Season (1997)	180.02 m above sea level	179.06 m above sea level	61 m	0.0157
Peak 3rd Season (1998)	179.76 m above sea level	178.88 m above sea level	61 m	0.0143
Late 3rd Season (1998)	179.67 m above sea level	178.75 m above sea level	61 m	0.0150
Peak 4th Season (1999)	179.83 m above sea level	178.9 m above sea level	61 m	0.0153

Cross Sectional Area Along Downgradient End of Planted Area

	Saturated Thickness - Well 526	Saturated Thickness - Well 527	Saturated Thickness - Well 528	Ave. Thick.	Aquifer Width	Cross Sectional Area
Baseline (November 1996)	1.59 m	0.80 m	1.22 m	1.20 m	70 m	84 m^2
Peak 2nd Season (1997)	1.50 m	0.80 m	1.20 m	1.17 m	70 m	82 m^2
Late 2nd Season (1997)	1.56 m	0.76 m	1.24 m	1.19 m	70 m	83 m^2
Peak 3rd Season (1998)	1.55 m	0.73 m	1.22 m	1.17 m	70 m	82 m^2
Late 3rd Season (1998)	1.56 m	0.75 m	1.23 m	1.18 m	70 m	83 m^2
Peak 4th Season (1999)	1.54 m	0.71 m	1.22 m	1.16 m	70 m	81 m^2

Average of TCE Concentrations In Wells Along Downgradient End of Planted Area

	TCE Concentration - Well 526	TCE Concentration - Well 527	TCE Concentration - Well 528	Ave. Conc.
Baseline (November 1996)	564 ug/L	610 ug/L	232 ug/L	469 ug/L
Peak 2nd Season (1997)	570 ug/L	685 ug/L	350 ug/L	535 ug/L
Late 2nd Season (1997)	NA	NA	NA	NA
Peak 3rd Season (1998)	530 ug/L	540 ug/L	380 ug/L	483 ug/L
Late 3rd Season (1998)	490 ug/L	470 ug/L	460 ug/L	473 ug/L
Peak 4th Season (1999)	NA	NA	NA	NA

[m above sea level, meters above sea level; m, meter; m^2, square meter; ug/L, micrograms per liter; NA, data not available]

[a] Slight differences between reported measurements and calculated gradients are due to rounding errors introduced during conversion of units from feet to meters for presentation in this table; calculated values were derived from measurements in original units of feet

Appendix B

Vendor's Section

Note: Information contained in this appendix was provided by the technology vendor and has not been independently verified by the U.S. EPA SITE Program

APPENDIX B – Air Force Experience and Recommendations

This section describes steps to be taken for implementing phytoremediation and establishing a short rotation woody crop. Knowledge of site-specific soil and climate conditions before planting can often decrease the probability of planting failure. This section has extensively utilized information developed by or for the Department of Energy's Biomass/Biofuel Program, Short Rotation Woody Crops Operations Working Group, and the Salix Consortia of the New York State Energy Research and Development Authority. Readers will also find additional lessons learned in the restoration of riparian zone vegetation, points of contact, helpful web sites, references to technical reports and handbooks, and sources of hybrid poplar, eastern cottonwoods, and willows are included in this section.

B.1 Introduction

Vascular plants have been on Earth over 400 million years. Flowering plants first emerged about 140 million years ago. Plants survive by exploiting their surroundings as they compete for light, nutrients and water. Plants have evolved various strategies that allow them to exploit a given ecological niche. Some plant groups are stress tolerators that can survive high salt and metal levels. Other plant groups compete "best" by growing rapidly. Because plants cannot readily move themselves from sites having adverse conditions, over time plants have developed the necessary biochemical processes to tolerate a variety of man made and natural carcinogens, mutagens, and teratogens. Some vegetation even has the ability to make compounds such as chloromethane. There are more than 3,200 chlorinated, fluorinated, and brominated chemicals produced by living organisms and natural combustion processes (Gribble). Chlorine is actually an essential element for plants. In fact, natural organohalogen compounds play an essential role in the survival of many organisms. Trees, shrubs, grasses, flowers and vegetables can readily handle low levels of halogenated hydrocarbons such as trihalomethane found in chlorinated drinking water. Another indication of this tolerance is that members of *Populus* and *Salix* families are often found in shallow ground water contaminated by trichloroethylene and its daughter products dichloroethylene, and vinyl chloride. Plants can do this because they have dehalogenase and mixed function oxidase enzymes needed to transform low levels of halogenated hydrocarbons.

Plants form the basis for agriculture and forestry. Plants have a long history of providing us with fuel, fiber, oils, medicines (quinine, digitalis, opiates), poisons (strynine, hemlock, etc.) and food. Perhaps the group to first exploit plants for environmental purposes was the Incas who planted alders in the 10th century to stabilize their planting terraces in Peru (Moore). Alders also helped maintain the fertility of the soil by fixing nitrogen. The Chinese have used trees since the 12th century to stabilize slopes and prevent erosion, while the Dutch have used trees to stabilize their earthen dikes for several hundred years. The ability of trees to act as pumps was noted in the late 19th century when *Eucalyptus* trees were planted in Italy and Algeria to dry up marshes. The incidence of malaria in these areas subsequently decreased.

Phytoremediation is a new term, but given the diverse and long history of plant exploitation through out world history it can hardly be considered a new idea. Phytoremediation is currently being practiced by some professionals with backgrounds in agronomy, biochemistry, hydrology, chemical engineering, sedimentology and industrial hygiene to clean up shallow groundwater and soil contaminated with various metals and organics. Because phytoremediation is in its commercial infancy, the people who employ phytoremediation have often designed projects with methodologies developed from personal experience. This knowledge is considered to be proprietary and zealously guarded even though much of this information is already in the public domain. About 30 years ago the United States Department of Energy embarked on a program to grow plants as a source of fiber and fuel in response to the Arab oil embargoes of the early 1970's. The outcome of millions of dollars and thousands of man years of effort is in an extensive body of public domain information on the physiology and development of short rotation woody crops. The information about individual species or clones that are most suitable for a given region, how to plant, control weeds, when and how often to fertilize, how to recognize and control plant pathogens and other pests, and how to harvest is all in the public domain. This public domain information gives detailed guidance on how to select and prepare potential sites. Research and development is also currently being conducted in the Netherlands, Finland, Denmark, Sweden, Italy, Australia, and the United Kingdom.

If shallow ground water contaminated with low level nitrates, phosphates, hydrocarbons, or chlorinated hydrocarbons is encountered at a site that is suitable to growing a short rotation woody crop, consideration should be given to employing the technology developed by the US DOE before employing any proprietary deep planting methods. This information is available on-line at the Biomass Information Network or through regional biomass energy programs.

Before initiating a phytoremediation corrective action for shallow ground water, it is imperative to determine if natural attenuation processes (i.e.,biodegration, dispersion, sorption, or volatilzation) are able to achieve site-specific remedial objectives within a comparatively reasonable time frame. If site-specific natural attenuation processes are at work and capable of reducing mass, toxicity, mobility or volume of halogenated hydrocarbons in the soil and groundwater, the site in question **MAY NOT** be considered a candidate for a phytoremediation intervention.

There are several currently available protocols and tools that have been developed by the United States Air Force, United States Geological Survey and Environmental Protection Agency to evaluate the fate of chlorinated hydrocarbons in the ground. *The Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater* has undergone extensive external and internal peer and administrative review by the U.S. EPA and U.S. Air Force. The intent of the Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater is to provide guidance for data collection and analysis to evaluate monitored natural attenuation through biological processes It is available from the National Technical Information Service. Another useful resource is BIOCHLOR Natural Attenuation Decision Support System available from the U.S. EPA Center for Subsurface Modeling Support (CSMoS). To obtain the BIOCHLOR program and user documentation go to the CSMoS web site at www.epa.gov/ada.csmos.html. Tables B.1 and B.2 show the parameters of interest when determining if natural attenuation is likely to occur in a given aquifer.

Table B.1

Analytical Parameters and Weighting for Preliminary Screening for Anaerobic Biodegradation Processes/

Analysis	**Concentration in Most Contaminated Zone**	**Interpretation**	**Value**
Oxygen*	<0.5 mg/L	Tolerated, suppresses the reductive pathway at higher concentrations	3
Oxygen*	>5 mg/L	Not tolerated: however, VC may be oxidized aerobically	-3
Nitrate*	<1 mg/L	At higher concentrations may compete with reductive pathway	2
Iron II*	>1 mg/L	Reductive pathway possible; VC may be oxidized under Fe(III)-reducing conditions	3
Sulfate*	<20 mg/L	At higher concentrations may compete with reductive pathway	2
Sulfide*	>1 mg/L	Reductive pathway possible	3
Methane*	<0.5 mg/L >0.5 mg/L	VC oxidizes Ultimate reductive daughter product, VC accumulates	0 3
Oxidation Reduction Potential* (ORP) against Ag/AgCl electrode	<50 millivolts (mV) <-100mV	Reductive pathway possible Reductive pathway likely	1 2
pH*	5 < pH < 9 5 > pH >9	Optimal range for reductive pathway Outside optimal range for reductive pathway	0 -2
TOC	> 20 mg/L	Carbon and energy source; drives dechlorination; can be natural or anthropogenic	2
Temperature*	$> 20^{o}C$	At T $>20^{o}C$ biochemical process is accelerated	1

Table B-1 continued

Carbon Dioxide	>2x background	Ultimate oxidative daughter product	1
Alkalinity	>2x background	Results from interaction between CO_2 and aquifer minerals	1
Chloride*	>2x background	Daughter product of organic chlorine	2
Hydrogen	>1 nM	Reductive pathway possible, VC may accumulate	3
Hydrogen	<1 nM	VC oxidized	0
Volatile Fatty Acids	> 0.1 mg/L	Intermediates resulting from biodegradation of aromatic compounds; carbon and energy source	2
BTEX*	> 0.1 mg/L	Carbon and energy source; drives dechlorination	2
Tetrachloroethene		Material Released	0
Trichloroethene*		Material released Daughter product of PCE	0 2[a/]
DCE*		Material released Daughter product of TCE. If cis is > 80% of total DCE it is likely a daughter product 1,1-DCE can be chemical reaction product of TCA	0 2[a/]
VC*		Material released Daughter product of DCE	0 2[a/]
1,1,1-Trichloroethane*		Material released	0
DCA		Daughter product of TCA under reducing conditions	2
Carbon Tetrachloride		Material Released	0
Chloroethane*		Daughter product of DCA or VC under reducing conditions	2
Ethene/Ethane	>0.01mg/L >0.1 mg/L	Daughter product of VC/ethene	2 3
Chloroform		Material Released Daughter Product of Carbon Tetrachloride	0 2
Dichloromethane		Material Released Daughter Product of Chloroform	0 2

* Required analysis. a/ Points awarded only if it can be shown that the compound is a daughter product (i.e., not a constituent of the source NAPL).

Table B.2 Interpretation of Points Awarded During Screening Step 1

Score	Interpretation
0 to 5	Inadequate evidence for biodegradation* of chlorinated organics
6 to 14	Limited evidence for biodegradation* of chlorinated organics
15 to 20	Adequate evidence for biodegradation* of chlorinated organics
> 20	Strong evidence for biodegradation* of chlorinated organics
	**reductive dechlorination*

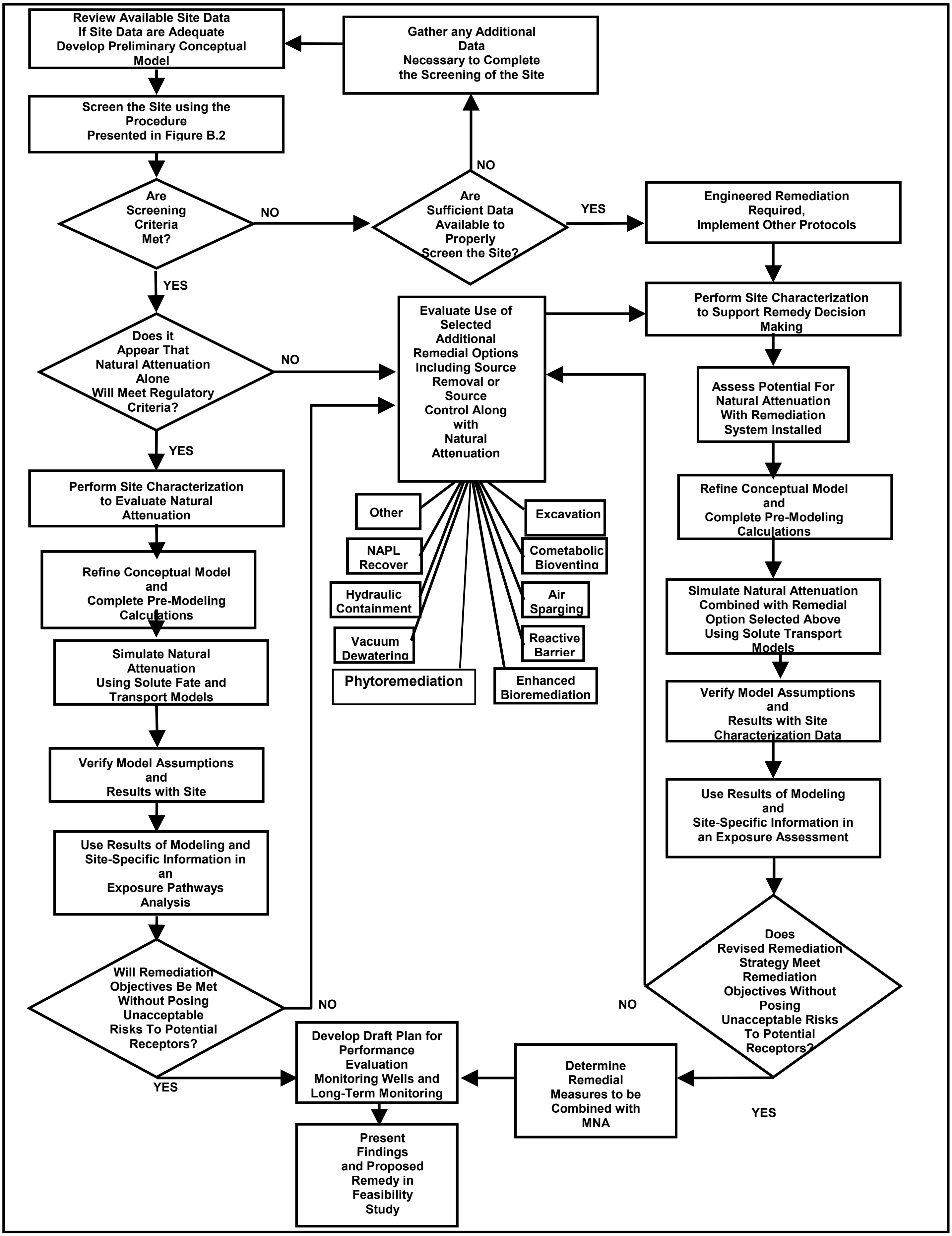


Figure B.1 *Natural attenuation of chlorinated solvents flow*

(Flowchart adapted from Technical Protocol for Evaluating Natural Attenuation of Groundwater)

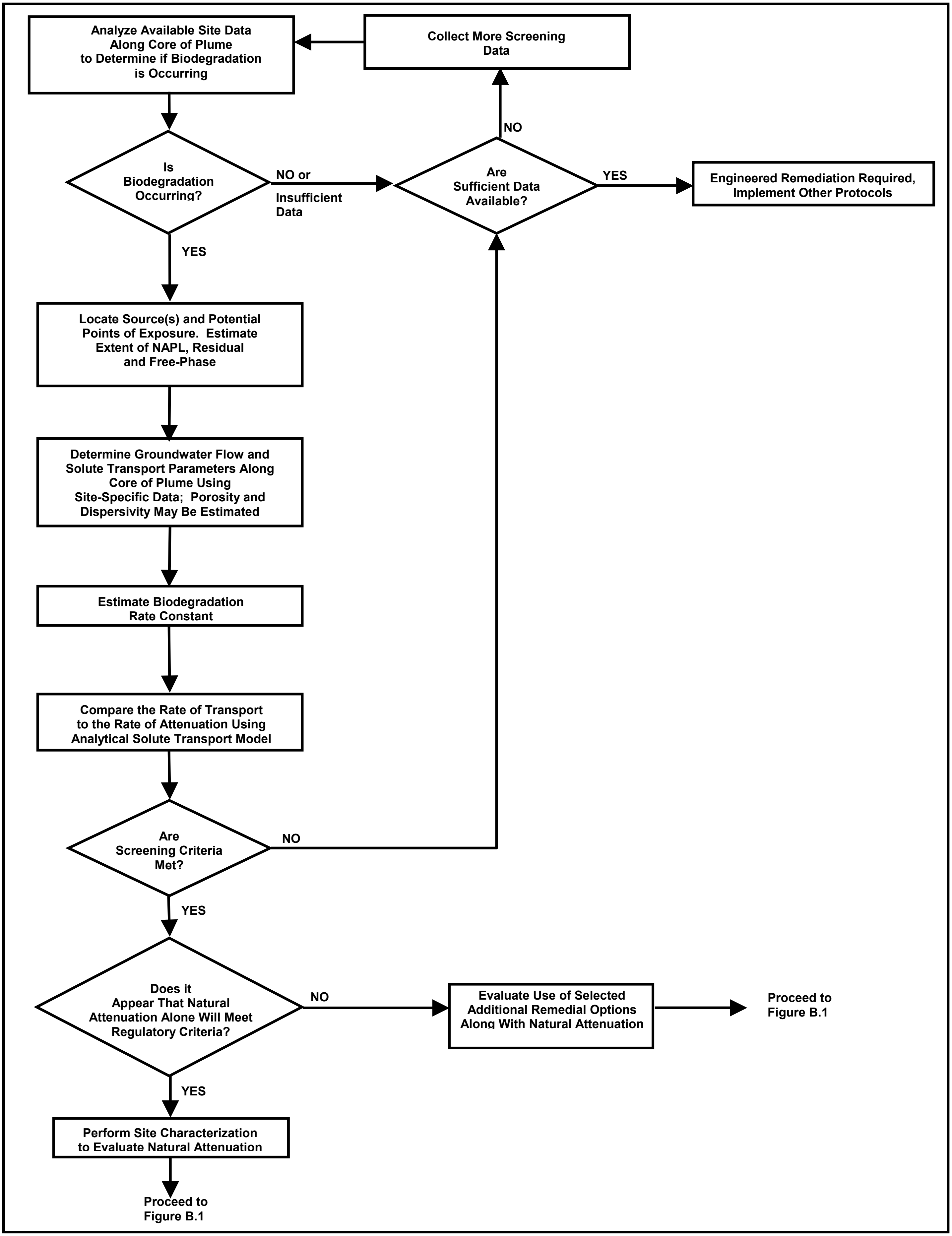
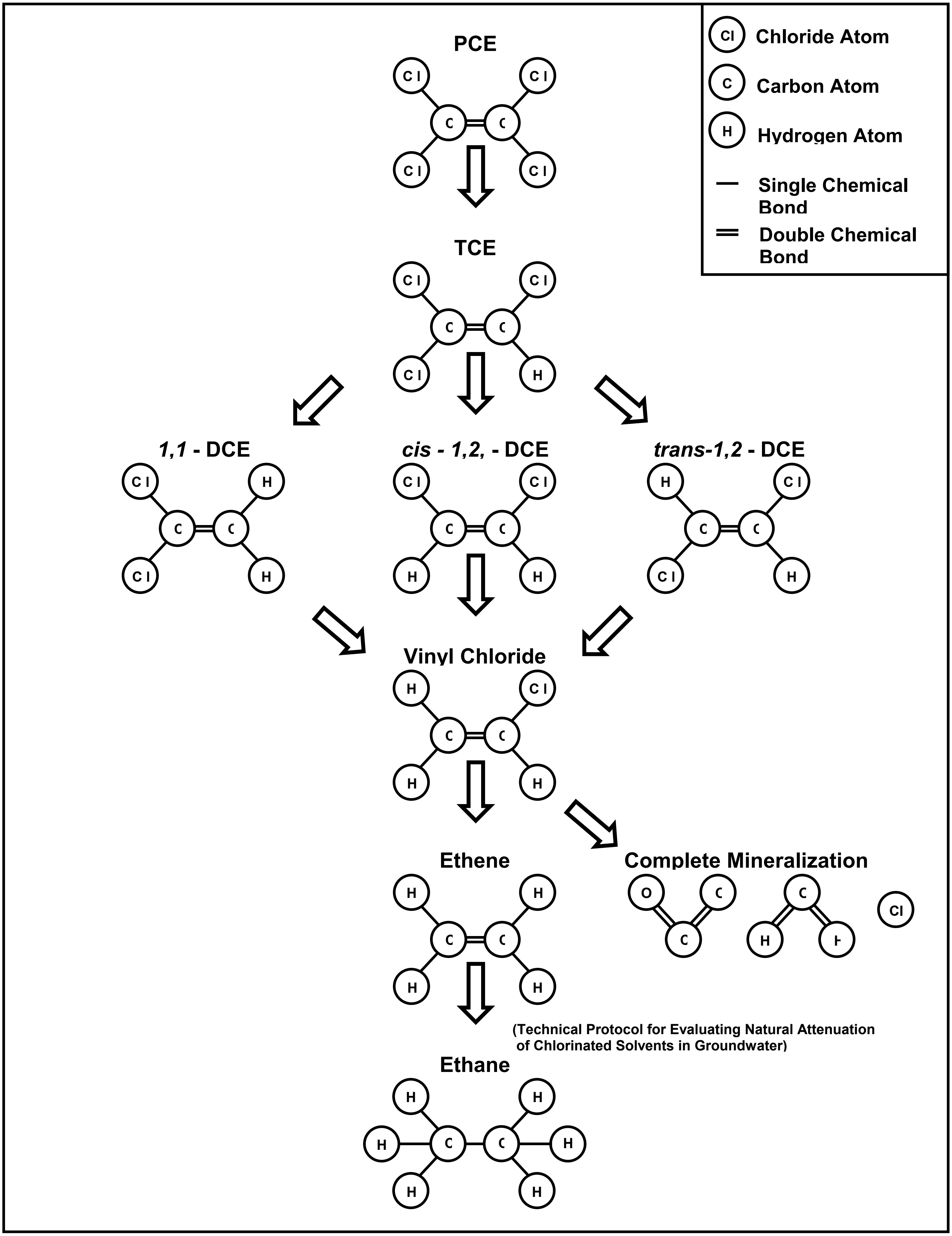


Figure B.2 *Initial screening process flow*

(Technical Protocol for Evaluating Natural Attenuation of Chorinated Solvents in Groundwater)



(Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater)

Figure B.3 *Reductive dehalogenation of chlorinated*

If the presence of any significant natural attenuation processes cannot be established from tables B.1 and B.2, the next step is to determine if the site is a candidate for the establishment of a short rotation woody crops. To determine if a site is viable for the establishment of a short rotation woody crop, a thorough understanding of site-specific hydrology and agronomic factors is essential. Failure to consider site- specific hydrologic factors such as pH, depth to groundwater and pattern of seasonal precipitation, and agronomic factors such as the nutrient status and presence of salts, soil compaction, and clay hardpans can lead to disappointment. While trees may grow at the site, there may be insufficient biomass to influence the geochemistry and hydrology of the groundwater. The establishment and management of a short rotation woody crop usually has the following goals:

1) Elimination of competing vegetation.
2) Maintenance of site productivity
3 Maximum net energy gain.
4) Maximum biomass for minimum cost

Whether a shallow groundwater site is suitable for development of short rotation crops such as cottonwoods, hybrid poplar, willow, eucalyptus, or other energy crops, requires consideration of operational factors such as location of the site, depth to groundwater, soil properties and climate. The sites should have sufficient area to plant the required biomass. Planting a few rows of trees may have subtle influences on groundwater flow. Keep in mind that the mere observation of diurnal variations in a water table does not imply hydraulic control. Potential sites should be level or gently sloping in order to use mechanical planting means whenever possible. If a site is near an airport or flight line, determine if Federal Aviation Administration (FAA) restrictions may limit height of trees. Small cuttings placed in the ground can eventually become 100 foot safety impediments to the operation of aircraft. The presence of large stones or construction debris may make large scale planting difficult and damage equipment. Another site factor is wet heavy clays that can make machine access difficult or impossible.

Hardpans are compacted soil that can tend to impair the ability of plants to send deep roots. Compaction of soil can result from vehicular traffic and natural cementation. If hardpans are present, deep ploughing may be necessary. There are vendors that specialize in ripping soil to correct this condition.

Site soil characteristics are also important for successful establishment of biomass. There are 16 nutrient elements that are essential for the growth and reproduction of plants. Thirteen of these essential elements may be supplied by the soil or supplemented by fertilizers. Plants obtain carbon, hydrogen, and oxygen from the air and water. Important soil properties are moisture and drainage, texture alteration, depth, pH, and fertility. Information on the characteristics of soil in a given county can be found from the Soil Conservation Service of the Department of Agriculture. These reports provide a general idea of the soils and climatic conditions in an area.

While soil surveys are an excellent starting point, it is strongly recommended that additional soil testing be conducted. Soil testing can provide site-specific answers to concerns about pH, salts and plant nutrient availability (i.e., nitrogen, phosphorus, potassium) and micronutrients such as manganese, iron, boron, zinc, copper, molybdenum, and chlorine. The first step is to select a laboratory to conduct the required tests. When selecting a soil testing laboratory, ask if they participate in a proficiency testing or quality assurance program. Ask to see the results of the most current evaluation. Most laboratories provide instructions on how to collect a representative soil sample. Laboratories offer a variety of soil analysis options. A routine analysis consists of pH, nitrates, phosphorus, potassium, calcium, sulfur, and conductivity. Additional testing options available at extra cost (typically $15 to $30) are analysis for micronutrients such as zinc, iron, copper, and manganese, detailed salinity testing, organic matter, texture, and boron.

A soil sample for testing should represent a uniform area. Past land use, drainage, slope, and differences in texture and color are important. Areas at the proposed site in which plants appear to be doing poorly should be tested separately. It is important to use a clean rust-free tool to avoid contaminating the soil sample with iron. Collect the sample from the soil surface to the depth desired. A clean plastic pail is a good container within which to mix soil samples. Avoid using galvanized or brass containers to prevent zinc contamination. Many soil testing facilities provide plastic bags for containing soil samples.

The pH of the soil is important because pH influences the availability of nutrients. Nitrogen is probably the nutrient that most often limits plant growth. Soil nitrogen is present in three major forms: elemental nitrogen, organic nitrogen, and nitrogen in fertilizers. Phosphorus (P) is an essential part of the process of photosynthesis.
Micronutrient deficiencies are most likely to limit plant growth under the following conditions:

1) Highly bleached acid sandy soil
2) Muck soils
3) Soil high in pH or lime content
4) Soils that have been intensively cropped and heavily fertilized with macronutrients

Some soil testing facilities provide only the results of the analysis while others also make specific recommendations based on the tests results for the crop to be grown. If recommendations are not provided by the laboratory, contact your local forester, county or state cooperative extension service for guidance. Once site-specific soil test recommendations have been made follow them. Do not apply more plant nutrients than recommended. This can create a nutrient imbalance that may adversely affect the plants being grown.

TABLE B.3

FACTORS THAT AFFECT THE PRODUCTIVITY OF SOILS FOR HARDWOODS

SOIL PROPERTY	BEST CONDITIONS	WORST CONDITIONS
Physical	Deep,>4ft, soils without pans. Loose, porous, friable soils (bulk density<1.4 g/cc). Undisturbed site with no recent cultivation or pasturing	Shallow, <1.5 ft, soils with plowpans or natural cemented pans. Strongly compacted, tight soils (bulk density >1.7 g/cc) pasturing for >20 years .
Moisture availability during growing.	Water table 3-6 ft. Level ground or lower slopes. No flooding or floods only early spring.	Water table <1 ft or > 10 ft. Ridgetops, mounds, dunes. Prone to flooding anytime.
Nutrient availability	Undisturbed site or cultivated <5 years. Organic matter (A-horizon) >3%, especially in sandy soils. A-horizon (topsoil) >6 in. Young, well-developed profile. Source of basic (calcareous) parent material in rooting zone. pH in rooting zone 5.0 – 7.5.	Recent intensive cultivation for >20 years. Organic matter (A-horizon) <1% A-horizon (topsoil) absent or <3 in. Old, highly leached profile. No basic (calcareous) parent material in rooting zone. pH in rooting zone <4.5 or >8.5.
Aeration	Wet by running water only in early spring. No mottling to 2ft. Soil color black, brown or red.	Swampy, stagnant or waterlogged condition much of year. Mottled to surface. Soil gray in color.

Table B.3 from The Culture of Poplars in Eastern North America by Donald Dickmann

Salt Stresses

Saline soils refer to a soil that contains sufficient soluble salts to impair its productivity. A soil is saline if the solution extracted from a saturated soil paste has an electrical conductivity of 4 decisiemens per meter Briggs). Saline soils are typically found in arid and semi-arid regions. Saline soils are rare in humid environments except in areas where the soil has been exposed to marine environments. In humid environments, soluble salts often migrate downward into the groundwater. Another source of salt to plants is from road de-icing salt spray that splashes or drifts onto the roadside. Plant damage from roadside salt spray is linked with the amount of salt applied and the traffic volume.

High salinity often limits plant growth by inducing water stress (Neuman). Plants exhibit a wide range of salt tolerance. Physiological esponses to salinity tend to be species specific (Newman). Some plants are very tolerant of salts (i.e., halophytes) while others are intolerant. Planting poplars or willows in areas with high soil salinity can be problematic (Briggs/Thomas). Soluble salts can produce harmful effects to plants by increasing the salt content of the soil solution and by increasing the degree of saturation of exchangeable materials (*USDA Agricultural Handbook 60*). The soluble salts that occur in soils consist of various amounts of sodium, calcium, magnesium and the anions chloride and sulfate (USDA Agricultural Handbook 60). The originof most salts are the primary minerals found in the soil and in the exposed parent rock of the Earth's crust.

Individuals attempting to plant vegetation in saline soils must carefully select vegetation that is appropriate. It is imperative that the planting material be adapted to the site-specific conditions. Failure to chose plant material phenotypically adapted to site conditions can often result in a planting failure (Briggs). Matching salinity tolerance to site-specific soil characteristics can be difficult (Briggs). Willows and poplars used for riparian revegetation were noted by Briggs to start exhibiting adverse effects when the salinity levels reach 2,000mg/l.

Flood Tolerance

Plants exhibit a wide range of tolerance to flooded or wet soil conditions. A site that is subjected to periodic flooding or wet soil conditions can impose very difficult conditions on most vascular plants. Some plants are much more tolerant of flooding and wet soil conditions than others. The fundamental difference between well drained and flooded conditions in the soil are directly and indirectly related to depletion of free oxygen (Whitlow). The absence of oxygen creates a reducing environment. Plants that are not adapted to wet or flooded soils exhibit reduced shoots and root growth and drop their leaves. Trees near rivers and streams are often subjected to flooding and wet soil conditions. Some plants can withstand complete inundation for months at a time, while others plants are completely flood intolerant. Flood tolerant plants have developed the anatomical, morphological and biochemical characteristics to withstand flooding and anoxic conditions. Factors that influence flood tolerance are the seasonal timings, duration, and depth of flooding. The seasonal timing of a flood is critical to the survival of trees and shrubs. Flooding when plants are dormant is usually not harmful. Flood tolerant and even intolerant trees like the tulip tree can withstand flooding when they are dormant. The time during which a flood occurs in the growing season, along with the depth and duration that an area is flooded can have a significant impact on the survival of developing vegetation. Within a given species, greater damaged and lower survival are associated with increased depth and duration of flooding.

Impacts of Temperature

Plants have an optimal temperature range at which they grow best. Many plants are susceptible to damage from freezing temperatures. The ability to withstand cold temperatures often limits the range of a given plant or even specific clones within a given species. Moving plant material north from southern latitudes can often be problematic. One 1976 study by Ying et. al. in Nebraska found that cuttings from Mississippi, Arkansas, and Texas suffered significant dieback during the winter. Ying et. al. concluded that trees from southern latitudes were more prone to injury in the winter because they retained their leaves late into the growing season. Another reason why plant material adapted to southern latitudes fail when moved hundreds of miles north is that they tend to leaf out earlier in the spring and are prone to damage from late frosts. To avoid these problems people attempting to establish phytoremediation plantations should know the origin of the plant material they purchase.

Wind

Living material grows in response to stresses that occur (Wood). The adaptive growth hypothesis states that a tree will grow only sufficiently strong to resist the forces that have occurred during its growth history (Wood). Wind is a ubiquitous component of the environment (Telewski). The mechanical failure of a tree is usually the result of wind rather than gravity (Vogel). Attempts to inhibit the growth of shallow lateral roots to enhance the growth of deep roots should be done with the knowledge that greater damage to tree stand productivity may be incurred from wind toppling in areas subject to high velocity winds. Wind can have profound effects on the growth and form of trees (Wind and Trees). Damage to short rotation woody crop plantations from high velocity winds is often an overlooked risk factor. Just as there are clonal differences in susceptibility to flooding and salinity, another abiotic stress is the mechanical stress from high velocity winds. Research by Harrington has shown that poplar clones proved resistant to toppling are associated with above and below ground characteristics. Harrington found that risk factors include trees that had less root system development in the wind ward quadrants. Wind toppling was the least at the closest spacing. This seems to be due to reducing crown sway. Toppling was also found by Harrington to be reduced in polyclonal plots which was believed to be the result of more rapid stand differentiation or reduction in the "domino effect" by inclusion of more wind resistant clones in the mixture. Hybrid poplars deep planted in Maryland with engineering controls to inhibit shallow lateral roots had almost a 20% incidence of toppling in the wake of Hurricane Floyd (Compton).

Maryland Wind Toppled Hybrid Poplar (Photo Courtesy of Harry Compton USEPA)

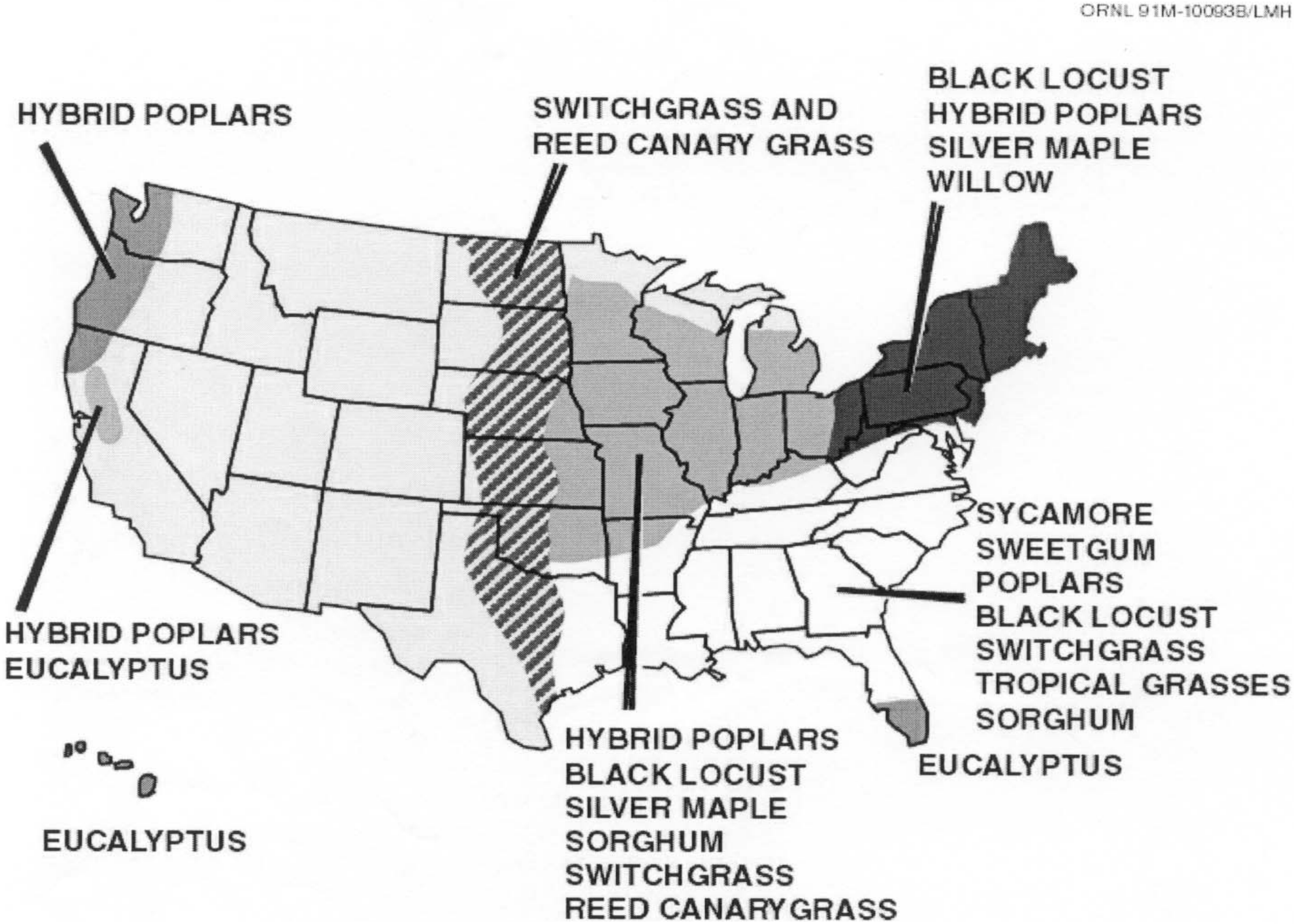
Biotic Stressors

Insects, fungi, viruses, bacteria, and gnawing animals can threaten the success and reduce the productivity of poplar and willow short rotation woody crops. Many readily available poplar trees are extremely susceptible to certain insect pests and diseases (Ostry). Symptoms of insect infestation and disease in poplar trees can be seen in off color foliage, missing foliage, branch die back, and cankers. Disease susceptibility among poplar clones is usually expressed by the second growing season (Hansen). Septoria cankers is more prevalent in the eastern United States and melansporia rust is more common in the western states. Trees severely stressed by one disease may ultimately be predisposed to other damaging agents such as other fungi, wood boring insects, and wind breakage. This predisposal is the case with trees severely affected by stem cankers (Hansen). While there are hundreds of insects and plant pathogens of poplars and willow, only a few are considered to be potentially dangerous (Ostry). Perhaps the most serious disease among poplar short rotation woody crops are stem canker diseases. Trees with stem canker infection often appear with dead, swollen, or shrunken patches on their stems (Dickmann). Sometimes the canker will stop and the wound will heal over time, but somtimes other fungal and bacterial infections will occur. Ready guidance about insect, disease and animal pest infestation of poplar trees is available in the *USDA Agricultural Handbook 677*. This handbook describes and illustrates with color photos the major insect, animal pests, fungal, viral, and bacterial diseases of poplars. This handbook enables growers of poplars to identify the causes of a problem should one develop. Being armed with this knowledge of the expected impact of the condition, control measures warranted, and what control measures are available enables a grower to effectively manage his crop. A careful examination of the affected trees should be made and compared to illustrative and descriptions within *USDA AgriculturalHandbook 677*. If a grower cannot determine the exact cause of problem with this handbook, it is advisable to consult a forest entomologist or forest pathologist (Ostry). Pest management information can also be obtained to Forest Service Offices listed at the end of this section.

Willows and cottonwood ecosystems are characterized by high diversity of both plants and animals (Briggs). Wildlife and vegetation have co-existed for millions of years in an on going struggle for survival by herbivores and plants. However, unlike declining water tables which can have a severe effect on trees wild life rarely significantly contributes to the decline of trees in a riparian ecosystem (Briggs). Some species like deer, rabbits, moles and beavers, however, can have an impact on newly established short rotation woody crop and riparian revegetation projects (Briggs). Moose, white tailed deer and beaver are all capable of eating large quantities of poplar and willow tree vegetation. Moose are only a problem to poplar plantations in northwest Minnesota and Sweden (Nester). Rodents such as moles, rats, and mice can also harm young shoots by gnawing off bark and damaging above ground irrigation lines. Rabbits and moles can be problematic in establishing poplar and willow plantations. In the Swedish experience, establishment of willow and poplar plantations can cause the existing population of rabbits and hares to significantly increase due to the ready abundance of food (Christersson). The best method for controlling rabbits and rodents has been to control weeds from the start of the plantation. When weeds are eliminated, moles, mice, rats, gophers and rabbits are vulnerable to potential predators.

Four hundred years ago there were approximately 60 to 100 million beavers in North America. The demand for pelts and heavy trapping pressure so severely impacted the beaver population of North America that by the 1800's beavers were extinct east of the Mississippi River. Today, however, beavers are making a come back through protective legislation and a lack of predators. Beavers are now moving into urban environments and near urban water ways, making their presence known in such diverse areas as Detroit, Ft Worth, and Washington D.C. to name a few. Beavers are gregarious and can usually be found in family groups. Young beavers leave their families at about two years. They find an area where young poplars grow and then they build a dam. Upstream they usually build a lodge and collect poplar branches for winter feed. Beavers are quite strong and can readily gnaw down and remove a thirty foot cottonwood tree almost over night. Beavers are also quite difficult to trap alive. Trapping beavers and moving them off site can require large amounts of time and effort and is usually only temporarily successful. Trapping beavers for their pelts is simply not as profitable as it used to be (Isebrands). Some states also frown on releasing live trapped beaver on to public lands. Efforts to control beavers include erecting regular fences and employing solar or battery power electric fences. Another approach has been to employ plastic shelter tubes 2-5 feet tall that allow the cuttings to grow. These preventative measures sometimes are successful but more often fail. Beavers at the Carswell Golf Course Phyto site have been an annual concern since 1996. Numerous trees have been damaged, but over all tree mortality to date has been very little. Willows and poplars readily sprout from cut or gnawed stumps. Virtually all poplars and willows coppice readily after beaver damage, harvesting or damage by fire (Dickmann). Since beavers are here to stay, beaver damage to established poplar and willow phytoremediation plantations should be taken in stride. Beaver damaged established poplar and willow trees will usually recover. While the above ground biomass is gone, subsurface biomass is still usually capable of establishing new above ground biomass. It has been our experience at Carswell that below ground short rotation woody crop biomass can still drive iron reducing conditions and reductive dechlorination of TCE in the absence of significant above ground biomass.

Beaver Damaged Trees **photo by Greg Harvey, USAF**



Map Courtesy of Virginia Tolbert (Oak Ridge National Laboratory)

For trees to reach their full genetic potential, plantation managers need to be able to select disease resistant clones and recognize various problems as they arise (Hansen). The goal of short rotation woody crops is to achieve and maintain high productivity (Mitchell). The Department of Energy has screened approximately 125 different plants as candidates for short rotation woody crops for fiber and fuel. The Department of Energy has found that certain species perform better than others in various regions of the United States. This finding is illustrated in the attached map of screened biomass candidates. After selecting the appropriate tree or trees for a given region, the next step is to select specific clones that give superior performance in a plantation. An understanding of short rotation woody crop production, stress, and ecophysiology has allowed plantation managers to achieve optimal clone-site matches at numerous sites (Mitchell). Tree breeders try to find clones that are adaptable to large areas (Hansen). Few clones however, are sufficiently stable for all situations in regions with varying soils and climates. Clones with desirable qualities such as superior growth rate and disease resistance can be selected from nursery screening trials. Promising clones selected from nursery screening trials are then planted in field trials.

Field trials are expensive and take several years to complete. Field trials have been conducted for hybrid poplars and cottonwoods by the United States Forest Service and for willows by the *Salix* Consortium of New York. Because of the time and expense involved, most poplar clones have not undergone field testing in all locations where they are now planted. The hybrid poplar field trials were conducted in eastern Ontario, the Pacific Northwest, and North Central sections of North American. A program for improving cottonwood was begun by the United States Forest Service in the early 1960’s after it became apparent that hybrid poplars from the Northeastern United States and Europe did not perform well

(Mohn). The results of the extensive hybrid poplar field trials pointed to clone stability throughout the North Central States and eastern Ontario, but site-specific stability in the Pacific Northwest (Hansen).

The greater stability of clones in the North Central eastern Ontario regions is believed to be due to a narrower climate range (Hansen). U.S. Forest Service found that clones DN 34, DN 17, and DN 182 in the North Central United States had reasonable disease resistance and biomass across a range of sites. Interestingly, Edward Hansen of the Forest Service noted that clone DN 182 performed well on sites with harsh dry conditions and also performed well on good sites with wetter conditions. But clones DN 34 and DN 17 that performed well on good sites were often affected more severely by disease on harsh sites. This observation was also noted in the Pacific Northwest field trials with other clones. The reason for the variability observed in the Pacific Northwest is believed to be that climate and soils vary greatly with distance from the ocean, elevation and which side of the Cascades Range.

The United States Forest Service has made several recommendations with respect to selecting clones for a site. First, potential tree growers should make clone selections based on their performance of half their projected rotation. Growers should not assume that because a tree grew eight feet the first year and is healthy that it is the "super tree" for a given area (Hansen). Second, poplar clones should be selected based on their performance in plantations. Singular trees grown in an open field are not a good indicator of plantation performance (Hansen). Additional information on hybrid poplar performance can be found in the *USDA Research Paper NC-320 North Central United States in Field Performance of Populus in Short Rotation Intensive Culture Plantations in the North-Central U.S.* Some vendors offer cuttings in various lengths ranging from 8 to 36 inches or more. It is often possible to get volume discounts by ordering large quantities. Typically the longer the cutting the more expensive it is. Prices for Spring 2000 for 8-9 inch hybrid poplar cuttings were approximately $ 0.25 each for quantities of 25 to 100 to approximately $0.16 for orders of 5000 cuttings or more. Spring 2000 prices for 18 inch cuttings were about $0.30 and 36 inch cuttings were about $0.50. Shipping and handling charges are usually extra. Because of the relative inexpense of cuttings in the establishment of a plantation one should order more cuttings than one anticipates planting. When ordering cuttings, preference should be given to male clones which do not produce seeds. Female poplar trees can produce large amounts of small wind borne seeds. These seeds can clog air conditioner heat exchangers, cover outdoor pools, and create other maintenance roblems for people living near poplars (Baldridge). Vendors of hybrid poplars in the Pacific Northwest and North Central United States are listed at the end of this section.

Willows are another species that have potential as a short rotation woody crop. Willows are easy to propagate, resprout readily after cutting, and are not susceptible to *Septoria* canker (White). *Septoria* canker has caused serious damage to hybrid poplar planted in New York and harvested on 5-10 year rotations (White). The field trials of various willow clones for biomass production was initiated in 1987 in central New York State by the State University of New York College of Environmental Science and Forestry, the University of Toronto, and the Ontario Ministry of Natural Resources. The most promising clone, willow clone SV1, in ultra-short rotation was found to yield 16 oven dry tons per hectare per year during the fifth growing season (Kopp). White's group found that fertilization significantly increased the rate at which clones reached their maximum biomass production. Kopp also noted large clonal variation in biomass production and survival. For further information concerning the availability of specific clone willow cuttings contact Timothy Volk of the State University of New York College of Environmental Science and Forestry, One Forest Drive Syracuse, New York 13210 tavolk@mailbox.syr.edu. There are two commercial sources of non-proprietary eastern cottonwood cuttings for sale to the public. One is the Crown Vantage cottonwood clonal nursery at Fitler, Mississippi and the other is Ripley County Farms in Doniphan, Missouri. Additional information on specific eastern cottonwood clones can also be found at the end of this section.

Storage

Careful site preparation and selection of appropriate planting material can be compromised by several things. Perhaps the simplest is improper storage of cuttings. Dormant cuttings improperly stored often fail to grow. For best results cuttings must be protected from heating and moisture loss and should be stored in sealed double plastic bags in a cold room or refrigerator just above 0 degrees C or 32 degrees F

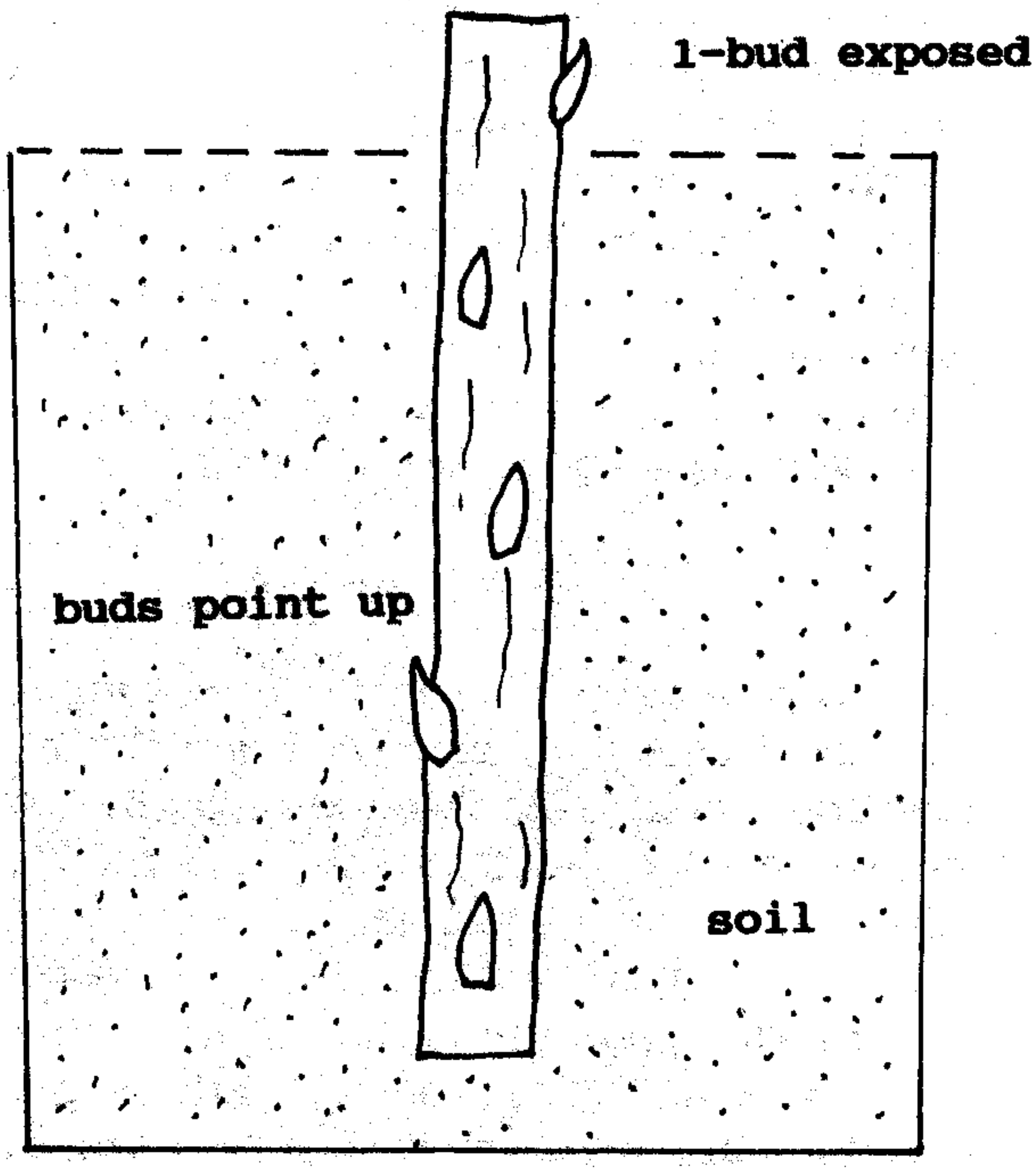
(Dickmann). It is important to warm cuttings slowly before they are planted (Dickmann). This is done by moving them to a room kept at 2 to 3 degrees C for a week or two prior to planting (Dickmann). Cuttings used for short rotation woody crop establishment in the North Central United States are usually 20 to 30 cm in length; 50 cm cuttings are the norm in the South and Pacific Northwest (Dickmann). Optimum diameters for cuttings range from 10-20 mm (Dickmann). On sites where moisture is limited in the upper most soil layer, the longer the cutting the better. Of course, it is seldom necessary to plant cuttings in excess of three feet long in the absence of hard pans. Cuttings should have numerous buds and be free of mechanical and insect damage (Dickmann). Cuttings that are spindly or have sprouted roots in storage should not be planted (Dickmann). For best results, cuttings should be warmed for 5-10 days prior to planting (Hansen) When soaking, it is important to make sure buds point up (Hansen).

Planting

The "best" time to plant cuttings is when soil temperature reach 50 degrees F (Hansen). In the North Central United States, planting usually occurs between mid April and early June (Hansen). In warmer places like the Carswell Site in Ft. Worth, Texas cuttings can be planted from late February to mid-May. Prior to planting, determine the location of above and below ground utilities, check if local ordinances prohibit some tree species, and decide if irrigation is necessary to supplement the natural soil moisture. Poplars and willows grow quickly and can obstruct the view of traffic if placed improperly. Special care should be exercised along roadways and intersections. Most cities encourage the planting of long-lived and low maintenance trees, but some local governments prohibit planting shorter-lived high maintenance trees. For example, the city of Ft. Worth prohibits planting hackberry, sycamore, silverleaf maple, mulberry, Arizona Ash, cottonwood, Siberan Elm and other high maintenance trees along city roadways. If a city prohibits a particular tree, a variance can often be obtained when there is an appropriate reason for using this type of tree.

Proper soil moisture and control of weeds are critical for a successful first year. The soil should be moist and the cuttings kept wet and protected from the sun while planting. Exposing cuttings to the sun for a prolonged period can significantly damage them prior to planting. It is important to remember to plant cuttings with their buds pointing up (Hansen). Buds must point up because this is the direction in which the tree will ultimately grow. Cuttings should also be oriented as close as possible to vertical (Dickmann). Cuttings must also have at least one bud exposed above ground (Hansen). Any air gaps around the cutting should be filled by pushing the soil against the cutting (Hansen). It is possible to plant cuttings by hand or to machine plant them. Usually small scale sites of a few acres are planted by hand and larger sites are planted by machine. Hand planting rates are reported by Hansen to be 3 acres/day/person and machine planting rates are 20 acres/day/three person crew. The trees at the Carswell Site were spaced at 8 by 8 feet in the five gallon bucket trees and 8 by 4 feet in the whip plantation. Spacing of the trees is often influenced by the number of years old they will be at harvest. The shorter the cutting cycle or rotation the closer the spacing of the trees. For poplars a cutting cycle of one to three years can have spacing of 2 by 2 to 4 by 4 feet. A rotation of 15 years can be spaced at 15 by 15 to 20 by 20 feet. For willows even closer spacing can be employed using the Swedish double row planting system. Keep in mind that closely spaced, genetically identical trees are prone to insect infestations and fungal diseases. Trees that are widely spaced apart, however, may take longer to root to the water table. A successful tree spacing design in phytoremediation achieves a balance where tree spacing promotes deep rooting without fostering conditions that encourage plant pathology problems.

Harvesting several rotations of a short rotation woody crop from a site can often result in a depletion of nutrients. Several different approaches to nutrient management for short rotation woody crops have been advocated (Heilman). The conservative approach is not overly concerned with the depletion of nutrients as long as production of above ground biomass is not significantly reduced (Heilman). The cost conservative school applies fertilizer only when soil fertility begins to impact growth. The other approach to fertilizing short rotation woody crops seeks to maintain fertility at a high steady state (Heilman). Here fertilizers are applied to not only supply nutrients but also to increase soil fertility (Heilman). The main drawback to this approach is the expense of maintaining high nitrogen levels and the risk of leaching nitrogen into the groundwater. Another drawback in phytoremediation applications of short rotation woody crops is that maintaining optimum levels of water and nutrients through irrigation and fertilization can decrease subsurface biomass (Dickmann). If trees are given optimum levels of nutrients and water it is unlikely that the tree will expend the resources to develop a large root system to explore the subsurface. Decreasing subsurface biomass may have an impact on the amount of carbon that is available for reductive dechlorination. Another problem with the liberal application of nutrients like nitrate is most studies show fertilizers are rarely 100% utilized by plants (Heilman). The liberal application of fertilizer in excess of what trees or other plants can use can cause leaching into the groundwater; this may impact the geochemistry of the groundwater making conditions unfavorable to reductive dechlorination. For these reasons, fertilizer applications to short rotation woody crops grown to phytoremediate shallow groundwater contaminated with halogenated solvents should only be done when foliar (leaf) level nitrogen levels fall below 3%. For further information about when to fertilize hybrid poplar platations obtain USDS Research Paper NC-319-A Guide to Determing When to Fertilize Hybrid Poplar Plantations.



Planted cutting.

Photo Courtesy of E. A. Hansen, et. al., 1992.

WEED CONTROL

Weed control is imperative during the establishment phase of a short rotation woody crop. The extensive experience of foresters throughout the world has shown that uncontrolled weeds can quickly compromise the success of a short rotation woody crop. Eliminating weeds reduces competition for light, water, and nutrient and also results in less cover for rodents (*Handbook of Short Rotation Woody Crops*). Omitting post planting weed control for hardwoods results in poor survival and growth and sometimes complete failure.

To insure a successful tree plantation, some short rotation woody crop foresters endeavor to have a 90% weed-free plantation in year one, 80% weed-free in year two, and 70% weed-free in year three. As the trees get bigger in the later years, they are better able to compete for light and water effectively, controlling the weeds.

There are a number of ways to control weeds by cultivation, mulching, and herbicides. One 1984 study by Edward Hansen *Research Note NC-317, Forest Service – U.S.P.A., titled, Weed Control for Establishing Intensively Cultured Hybrid Poplar Plantation* compared eight weed control methods that included cultivation, herbicides, and a legume cover by themselves or in various combinations. The weed control treatments were as follows:

Glyphosate
Linuron – Legume
Linuron – Glyphosate
Linuron – Cultivation
Cultivation
Legume
Furrow Cultivation
Furrow Cultivation

Hansen concluded that there was no difference in survival among poplar trees for six of the eight treatments. The weed control treatment significantly affected first year height. Hansen states that from the standpoint of tree survival and growth ,the pre-emergent herbicide lenuron applied alone or combined with other treatments gave consistently superior performance.

Glyphosate was found to be extremely difficult to apply after planting without damaging tree seedlings. Actively growing young hybrid poplars are easily damaged by even small amounts of glyphosate spray but are not affected through the soil (Hansen). Glyphosate damage is manifested in off color leaves and stunted growth.

Other researchers in Canada, Sweden, Italy, and the United Kingdom seem to agree that herbicides are consistently the most effective and cheapest means of providing the necessary degree of weed control. In contrast, mechanical cultivation must be done every 10-14 days to be effective. Manual weed control does not appear to be a viable economic option for large scale poplar plantations at this time. Manual weeding is labor intensive and is something to be avoided if possible even in small scale operations.

The actual choice of herbicide and application method chosen appears to depend chiefly on the nature of the weed problem and the timing of the application. Keep in mind that dry weather may render pre-emergent herbicides ineffective. A cautionary note is that laws regulating the use of herbicides differ from country to country. In America, regulations require the listing of a crop species on the herbicide label before it can be used legally on a commercial or private basis (*Handbook of Short Rotation Woody Crops*). Herbicide labels are constantly changing and one should also consult specific product labels and information before applying any herbicide. On smaller scale for plantings near wetlands or other sensitive areas, the use of plastic microfunnel mulches may be another option to consider. Ultimately, the level of weed control required will depend on the area to be planted, the time of year, and whether weeds are primarily annuals or perennials. A more in-depth review of weed management in short rotation woody crops is provided in a 1998 paper, "*Weed Management in Short Rotation Poplar and Herbaceous Perennial Crops Grown for Biofuel Products*" by Douglas Buhler.

Irrigation

The decision whether to irrigate or not can often be difficult. One must consider such factors as the depth to ground water, the amount of annual precipitation and the timing of this precipitation. Some places like Ft. Worth, Texas receive most of their precipitation in the spring and fall. Places with only sporadic, scattered rain in the summer can make the establishment of cuttings difficult because they lack an adequate root system. An understanding of historic weather patterns is required to make an informed decision on whether to install an irrigation system in a given area. Fortunately, free world-wide historical climate data can be obtained on-line from the Utah Climate Center at Utah State University at http://climate.usu.edu/free.

Supplemental water should be applied if soil moisture falls below 75 to 80 per cent of field capacity of below –0.05 to –0.1M Pa (0.5 to – 1.0 far) of tension (Dickman). Another approach is to irrigate whenever weekly precipitation fails to reach a certain minimum amount (Dickman). Tensiometers installed at a depth of 18 and 60 inches are a good way to assess the amount of available soil. There are numerous ways to apply supplemental water. Flood irrigation is the most economical but is restricted to level terrain and soil with high water holding capacity.

Large scale short rotation woody crop plantations in the Pacific Northwest employ drip irrigation systems that deliver millions of gallons of water per day derived from the Columbia River. Drip irrigation allows application of precise amounts of water to plant roots (New). This allows soil moisture in the area around the plant to be maintained at a uniform level throughout the growing period (New). Drip irrigation is used more often for orchard crops than for field crops (New). Drip irrigation was employed at the Carswell site during the first growing season. Without this irrigation system, the plantations at Carswell would have failed because the summer of 1996 was one of the driest summers on record in Texas.

Many planted trees are able to reach groundwater 3m below the surface when irrigated for the first two seasons after having been planted (Briggs). This was also our experience at the Carswell site. A root study conducted by the University of Georgia found that both plantations at the Carswell site had reached the saturated zone in September of 1997, seventeen months after planting (Hendrick). There are numerous ways to install an irrigation system at a site. Tree roots usually only explore moist soil so when the irrigation system is turned off roots can often be left high and dry above the water table or saturated zone. First plantings should be irrigated the first growing season. The length of irrigation and the amount depend on how long it takes tree roots to reach the saturated zone. Typically, young growing cottonwoods require 5-8 gallons a day per tree. (19-30 liters/day/tree) Experience in the restoration of riparian vegetation in the arid western United States has shown that the most reasonable irrigation strategy to give trees an over abundance of water so that soil is saturated to groundwater nearly constantly (Briggs).

The typical components of a drip irrigation system are a main pipeline which carries water to manifolds and lateral lines. Water flow is regulated using manual or automatic valves. Guidance on how to plan and operate an orchard drip irrigation system can be obtained in the *booklet Planning and Operating Orchard Drip Irrigation Systems B-1663* from the Texas Agricultural Extension Service at Texas A&M University System in College Station, Texas. This booklet addressees drip irrigation system layout, salinity management, emitter clogging control, fertilizer injection, and backflow prevention.

Salinity management is important because water from streams and aquifers usually contain dissolved salts. Application of groundwater can add salt to the soil where it will accumulate unless it is moved below the root zone by rainfall or excess irrigation water (New). When the amount of salt added exceeds the amount removed by leaching salts, the concentration in the soil can become harmful to trees and other plants (New). This process, called salinization, has caused the collapse of agriculture in many ancient and modern societies (Hillel). Irrigation water is considered poor quality when it contains moderate to large amounts of salt. Before irrigating a phytoremediation plantation with water from a contaminated deep aquifer it is important to know the amount of salts in this water (New). It is important not to guess about soil and water quality. It is advisable to have an annual salinity analysis of soil samples from the root zone to insure the long term productivity of a phytoremediation plantation irrigated with deep contaminated water.

Emitters employed in drip irrigation frequently clog from physical, biological, and chemical processes. Clogging reduces water emission rates and can cause stress to plants by non-uniform water distribution (New). Physical clogging is caused by soil, sand, pipe scale, and plant material and can be prevented by employing a filter system that is appropriate for the emitter type and size (New). Filters with multi-stage corrosion-resistant screens may be required when irrigation water contains large amounts of sand. Biological clogging is usually in the lateral lines and is caused by microorganisms and algae. Biological clogging is reduced by selecting emitters with large orifices and flushing the system with a chlorine concentration between 10-50 ppm (New). High concentrations and the precipitation of calcium, magnesium, and iron in irrigation water causes chemical clogging (New). Concentrations of calcium and magnesium greater than 50 ppm in irrigation water often requires periodic injections of hydrochloride solution throughout the growing season (New).

Back flow occurs when the flow of water is reversed from an irrigation system back into a potable water supply system. If contaminants are allowed to flow back into the potable water system it is possible to create a public health problem. The prevention of backflow in irrigation is very important. It is important to have an understanding of how to prevent backflow. Any connection between a potable water supply and a potential source of contamination is termed a cross-connection. Backflow or the reverse flow of liquids in a plumbing system is caused by two basic conditions backpressure or backsiphonage. The most likely causes of backpressure; are a booster pump designed without backflow prevention devices or interconnection with another system operated at a high pressure such as a fertigation injector system. When a change of system pressure causes the pressure at the supply point to become lower than the pressure at the point of use non-potable water can be backsiphoned into the main line. The main causes of backsiphonage are undersized piping, line repairs or breaks that are lower than a service point, lower main pressure from high water withdrawal rates and reduced supply main pressure on the suction side of a booster pump. Pollutants can be controlled at the cross-connection by one of several mechanical backflow preventers such as atmospheric or pressurized vacuum breakers, double check-valve assemblies, and a reduced pressure principle assembly. The type of backflow preventer required is based on the risks posed by the substance which may flow into the potable water supply system. Local and state regulations for codified construction requirements need to be checked. All backflow preventers should be inspected after installation and checked annually to insure their proper function and operation.

MONITORING LESSONS LEARNED

The monitoring of groundwater at the Carswell Site has produced several insights. The first is that traditional groundwater level measuring devices will likely cease to operate properly or give erroneous readings due to roots from the planted cuttings hanging them up. The iron in the steel float can interact with the groundwater to produce greatly elevated hydrogen levels. This is an artifact and doesn't reflect the influence of the plantation subsurface biomass on the geochemistry of the groundwater. The problems with traditional floats were resolved at the Carswell Site by employing Design Analysis WATERLOG H310 pressure sensors. These cost approximately $1000 a piece and work by detecting changes in flow which correlate to changes in pressure. It is important that this pressure sensor be clamped or tied down to fixed location where there is no velocity flow. If the pressure is subject to open flow it is likely that the readings will be inconsistent (Rivers). This no flow condition is achieved by suspending the sensor from a stainless steel drop cable and using a weighted ballast or sinker (Rivers).

Where Can I Order Hybrid Poplar Cuttings?

Lee Wholesale Nursery Fertile, MN 56540 (218) 574-2237	Lincoln-Oaks Nurseries Box 1601 Bismark, ND 58501
Schumacher’s Nursery & Berry Farm 711 Chapman Avenue Route 2 Box 10 Heron Lake, MN 56137 (507) 793-2288	Mike Hradel Cold Stream Farm 2030 Free Soil Road Free Soil, MI 49411 (616) 464-5809
Jamie DeRosier Route 1 Box 310A Red Lake Falls, MN 56750 (218) 253-2861	Insti Trees Nursery Box 1370 Rhinelander, WI 54501 (715) 365-8733
Hramor Nursery 515 9th Street Manistee, MI 49660 (616) 723-4846	Pope SWCD 24 First Avenue SE Glenwood, MN 56334 (320) 634-5326
East Otter Tail SWCD 655 3rd Avenue Southeast Perham, MN 56573 (218) 346-2050	MN Agro-Forestry Coop c/o WesMin RC&D Council 900 Robert Street, #104 Alexandria, MN 56308 (320) 763-4733
Mt Jefferson Farms, Inc. P.O. Box 12708 Salem, OR 97309 (503) 363-0467	Segal Ranches 2342 S. Euclid Road Grandview, WA 98930 (509) 882-2146

WHERE TO GET EASTERN COTTONWOOD CUTTINGS

Eastern Cottonwood (P. deltoides)

Non-Proprietary Planting Stock

- 110804
- 110610
- 110412
- 110226
- ST75
- ST72
- ST70
- ST66
- S7C20
- S7C15
- S7C8
- S7C1

CROWN VANTAGE
FOREST RESOURCES
5925 NORTH WASHINGTON STREET
VICKSBURG, MS 39183
OFFICE: (601) 630-9899
FAX: (601) 636-5865

NOTE: ST clones were developed by Stoneville Lab

S7C clones originated in Texas

110 clones originated from various sandbars along the Mississippi River

Non-Proprietary Cottonwood Cuttings

Harrison Wells
Ripley County Farms
P.O. Box 614
Doniphan, MO 63935
(573) 996-3449
rcf@semo.net

Forest Service Offices

Region 1 – Northern

USDA Forest Service
State & Private Forestry
Forest Pest Managaement
Federal Building
P.O. Box 7669
Missoula, MT 59807
(406) 329-3511
FTS 585-3511

Region 2 – Rocky Mountain

USDA Forest Service State & Private Forestry
Forest Pest Management
11177 W. 8th Ave.
Box 25127
Lakewood, CO 80225
(303) 236-3213
FTS 776-3213

Region 3 – Southwestern

USDA Forest Service
State & Private Forestry

Region 6 – Pacific Northwest

USDA Forest Service
State & Private Forestry
Forest Pest Management
319 S.W. Pine St.
P.O. Box 3623
Portland, OR 97208
(503) 221-2877
FTS 423-2727

Region 8 – Southern

USDA Forest Service
State & Private Forestry
Forest Pest Management
1720 Peachtree Road N.W.
Atlanta, GA 30367
(404) 347-2989
FTS 257-2989

USDA Forest Service
State & Private Forestry
Forest Pest Management
2500 Shreveport Hwy.
Pineville, LA 71360

Northeastern Area

USDA Forest Service
State & Private Forestry
Forest Pest Management
370 Reed Road
Broomall, PA 19008
(215) 461-3252
FTS 489-3252

USDA Forest Service
State & Private Forestry
Forest Pest Management
Louis C. Wyman For. Sci. Lab.
P.O. Box 640
Durham, NH 03842
(603) 868-5719
FTS 834-5765

USDA Forest Service
State & Private Forestry
Forest Pest Management
180 Canfield St.
P.O. Box 4360
Morgantown, WV 26505
(304) 291-4133

Forest Pest Management
Federal Building
517 Gold Ave. S.W.
Albuquerque, NM 87102
(505) 842-3292
FTS 476-3292

Region 4 – Intermountain

USDA Forest Service
State & Private Forestry
Forest Pest Management
Federal Building
324 25th St.
Ogden, UT 84401
(801) 625-5257
FTS 586-5257

Region 5 – Pacific Southwest

USDA Forest Service
State & Private Forestry
Forest Pest Management
630 Sansome St.
San Francisco, CA 94111
(415) 556-6520
FTS 556-6520

(318) 473-7160
FTS 497-7160

USDA Forest Service
State & Private Forestry
Forest Pest Management
200 Weaver Blvd.
Asheville, NC 28804
(704) 672-0625
FTS 672-0625

Region 10 – Alaska

USDA Forest Service
State & Private Forestry
Forest Pest Management
Federal Office Building
Box 1628
Juneau, AK 99802
(907) 261-2575
FTS 907-261-2575

FTS 923-4133

USDA Forest Service
State & Private Forestry
Forest Pest Management
1992 Folwell Ave.
St. Paul, MN 55108
(612) 649-5261
FTS 777-5261

REGIONAL BIOMASS ENERGY PROGRAM

The Regional Biomass Energy Program (RBEP) carries out activities related to technology transfer, industry support, resource assessment, and matches local resource to conversion technologies. Activities are conducted by five regional programs (Northwest, Western, Great Lakes, Southeast and Northeast) that promote development of biomass energy conversion technologies and feedstocks that are applicable to the region.

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Fred J. Kuzel **Great Lakes Regional Energy Program** 35 E. Wacker Drive, #1850 Chicago, IL 60601 (312) 407-0177(phone), (312) 407-0038 (fax) fkuzel@cglg.org (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin)	**Jeff Graef** **Dave Waltzman** P.O. Box 95085 Lincoln, NE 68509-5085 Graef: (402) 471-3218, fax (402) 471-3064 Jgraef@mail.state.ne.us Waltzman: (303) 275-4821, fax (303) 275-4830 Dave.waltzman@hq.doe.gov (Arizona, California, Colorado, Kansas, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, south Dakota, Texas, Utah, and Wyoming)

Richard Handley **Northeast Regional biomass Program** Coalition of Northeastern Governors 400 North Capital St., NW Suite 382 Washington, D.C., 20001 (202) 624-8454 (phone), (202) 624-8463 (fax) nrbp@sso.org (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont)	**Jeff James** **Northwest Regional Biomass Energy Program** 800 5th Ave, Suite 3950 Seattle, WA 98104 (206) 553-2079 (phone), (206) 553-2200 (fax) jeffrey.james@hq.doe.gov (Alaska, Idaho, oregon, Montana, and Washington)
Phillip Badger **Southeast Regional Biomass Energy Program** P.O. Box 26 Florence, AL 35631 (256) 740-5634 (phone), (256) 740-5530 (fax) pcbadger@mindspring.com (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, Virginia, West Virginia, Washington, DC)	More RBEP information and reports are available at the Biomass Resource Information Clearinghouse.

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