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-

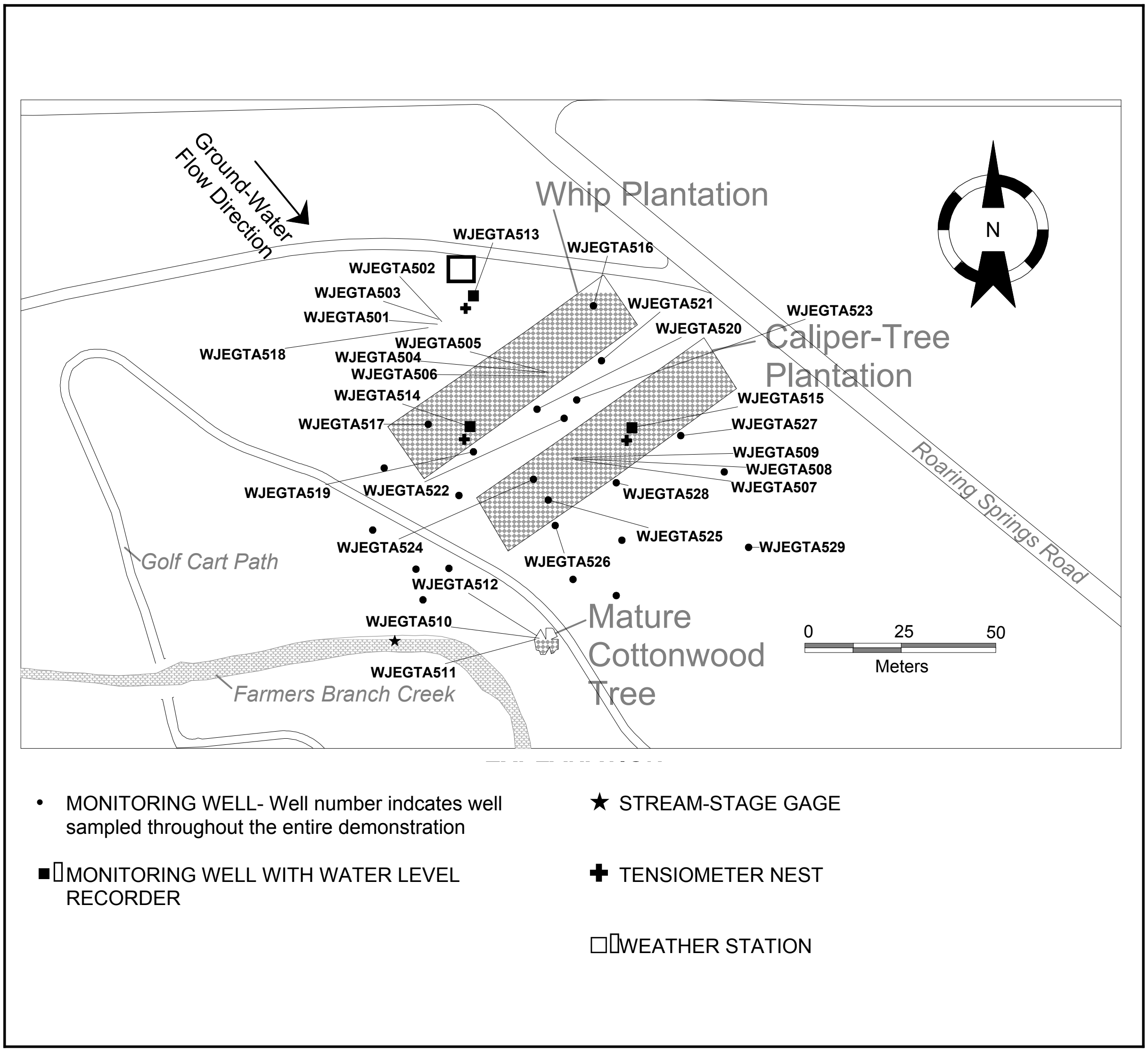

Figure 4-1. Short Rotation Woody Crop Groundwater Treatment System site layout.

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.)

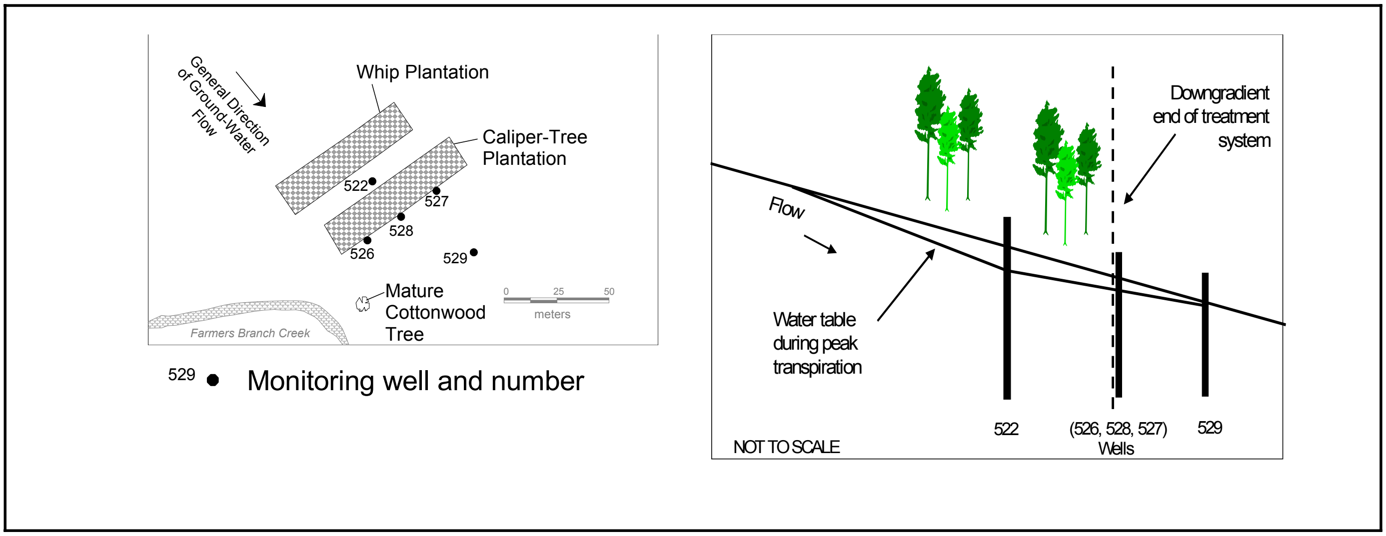

Figure 4-2. Wells used to monitor for changes in the volumetric flux of groundwater across the downgradient end of the Short Rotation Woody Crop Groundwater Treatment system.

- 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.

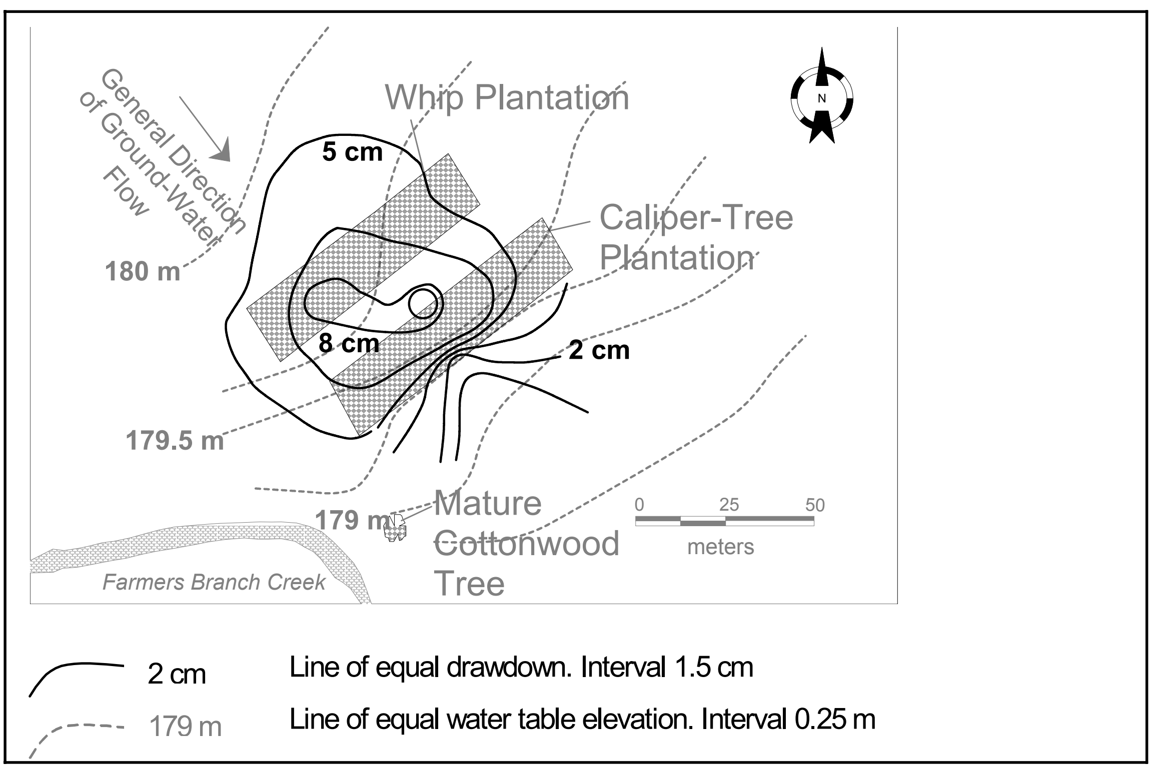

Figure 4-3. Drawdown at the water table that can be attributed to the trees, June 1998.

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

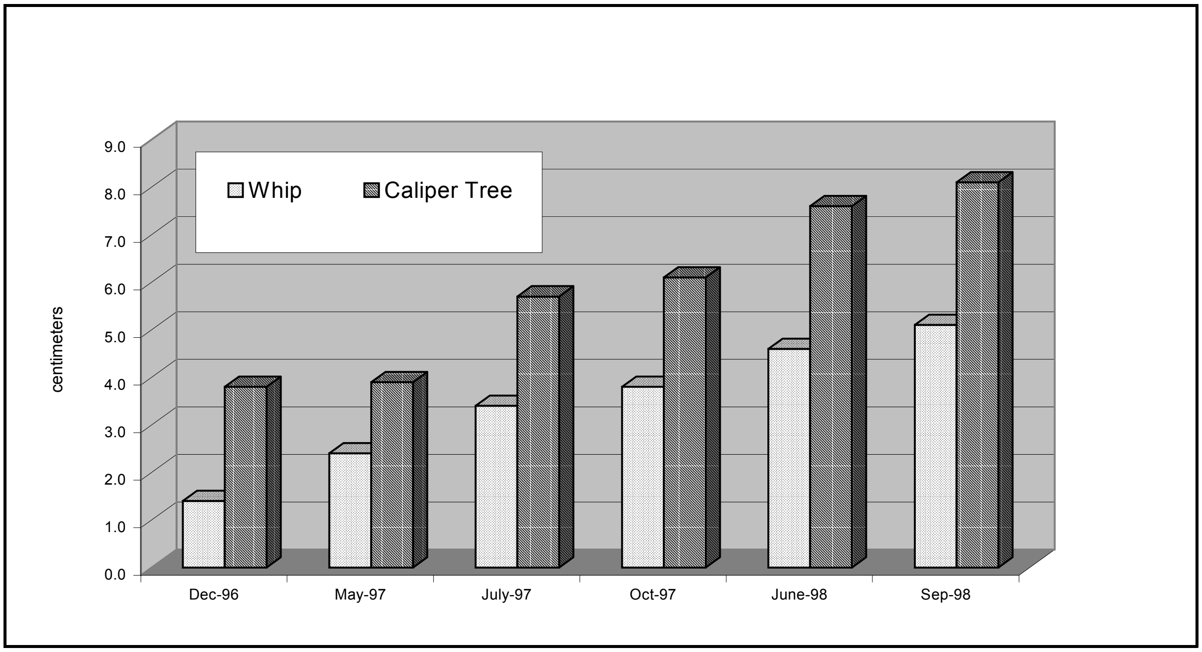

Figure 4-4. Trunk diameter over time.

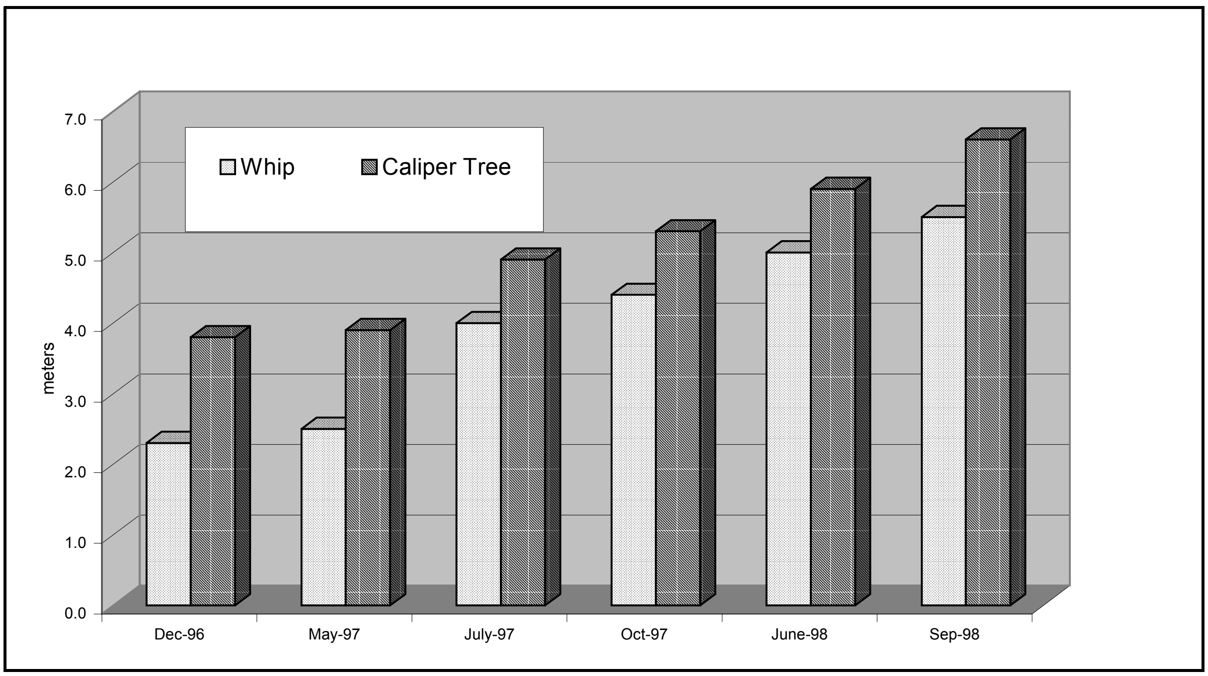

Figure 4-5. Tree height over time.

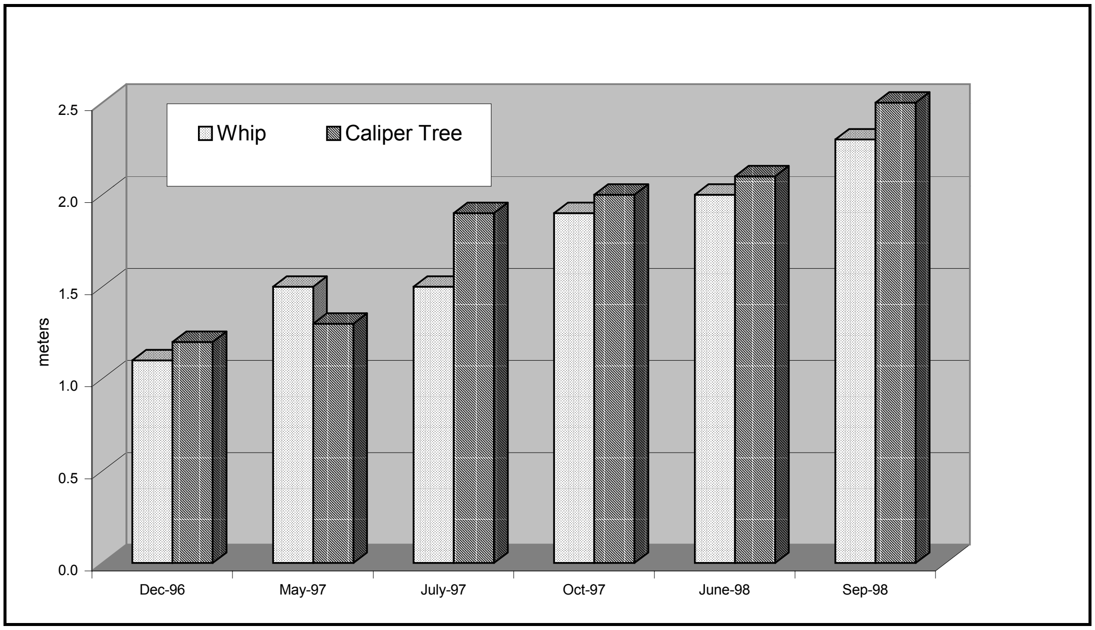

Figure 4-6. Canopy diameter over time.

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

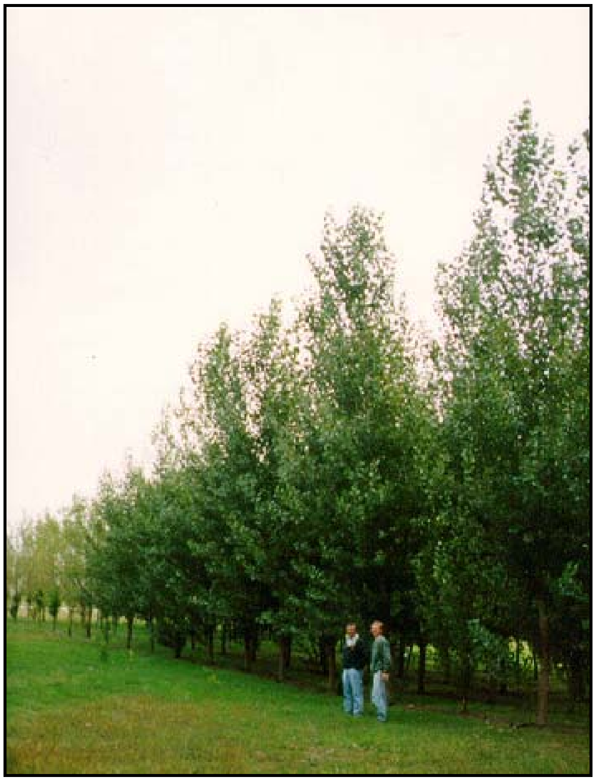

Figure 4-8. Caliper-tree plantation at the end of the third growing season, October 1998.

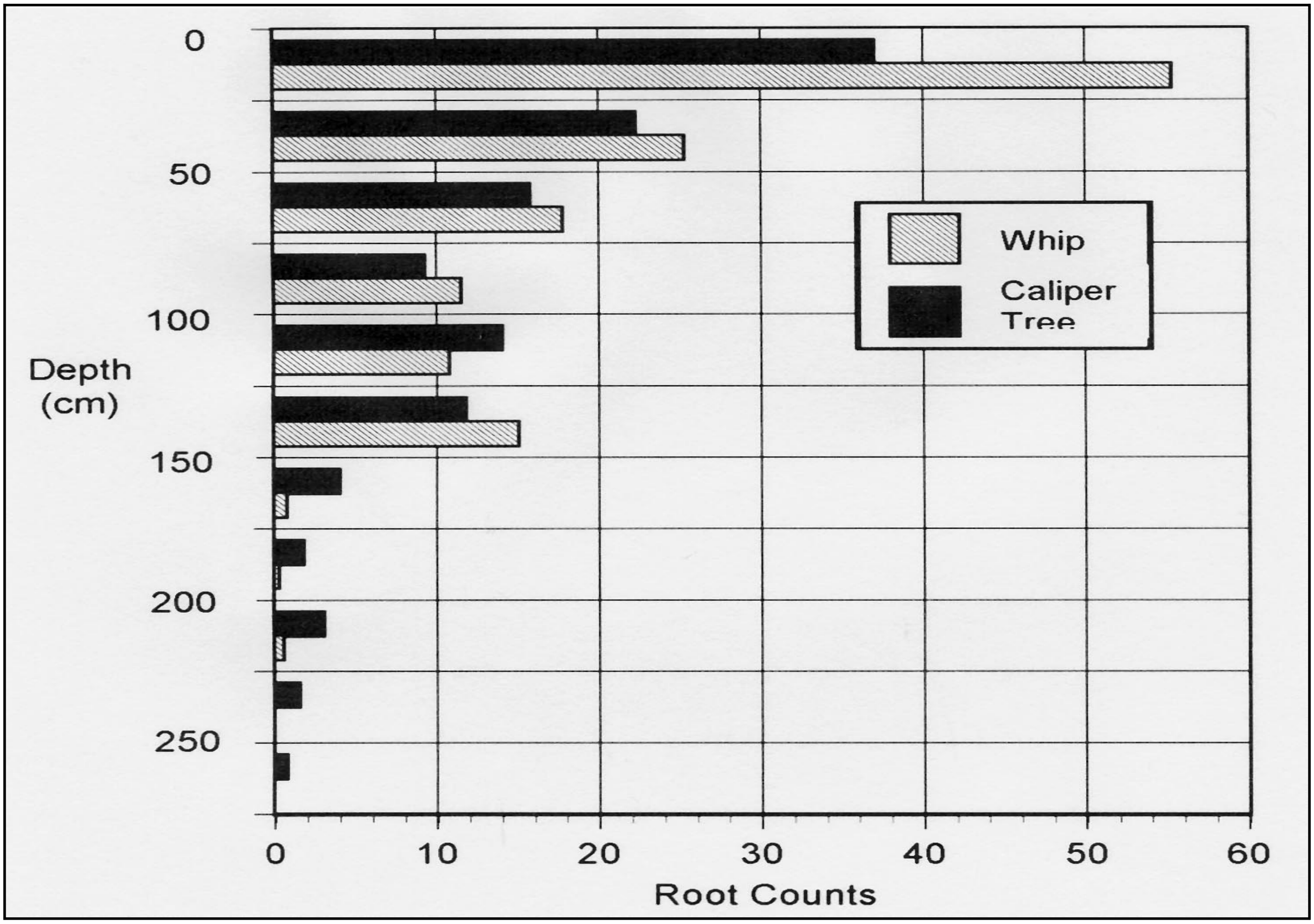

Figure 4-9. Root counts by depth.

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

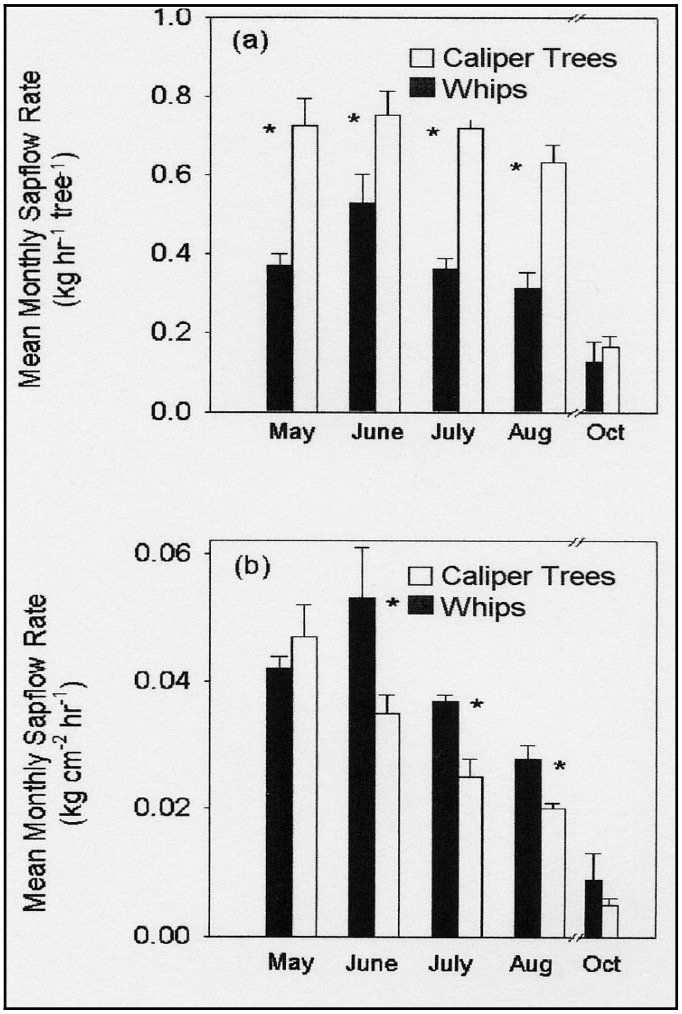

Figure 4-10. Variation in mean hourly sapflow rate (a) expressed on a per tree basis and (b) expressed on a per unit basal area basis. Data are sample period means for all months ($p<0.05$) differences between whips and caliper trees are denoted by *. Vertical lines on all bars represent standard errors.

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

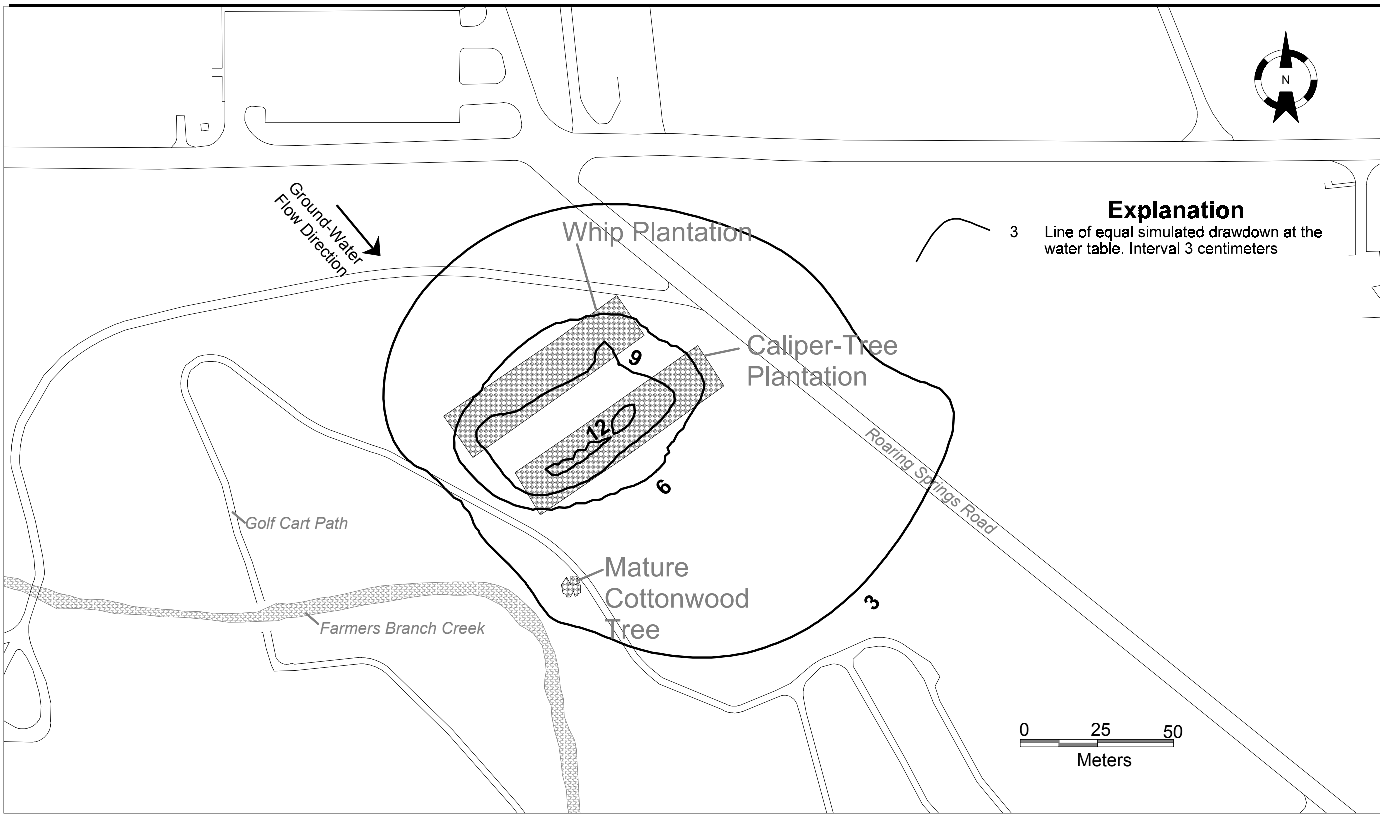

Figure 4-11. Minimum predicted drawdown at the water table for closed-canopy conditions (year 12 and beyond).

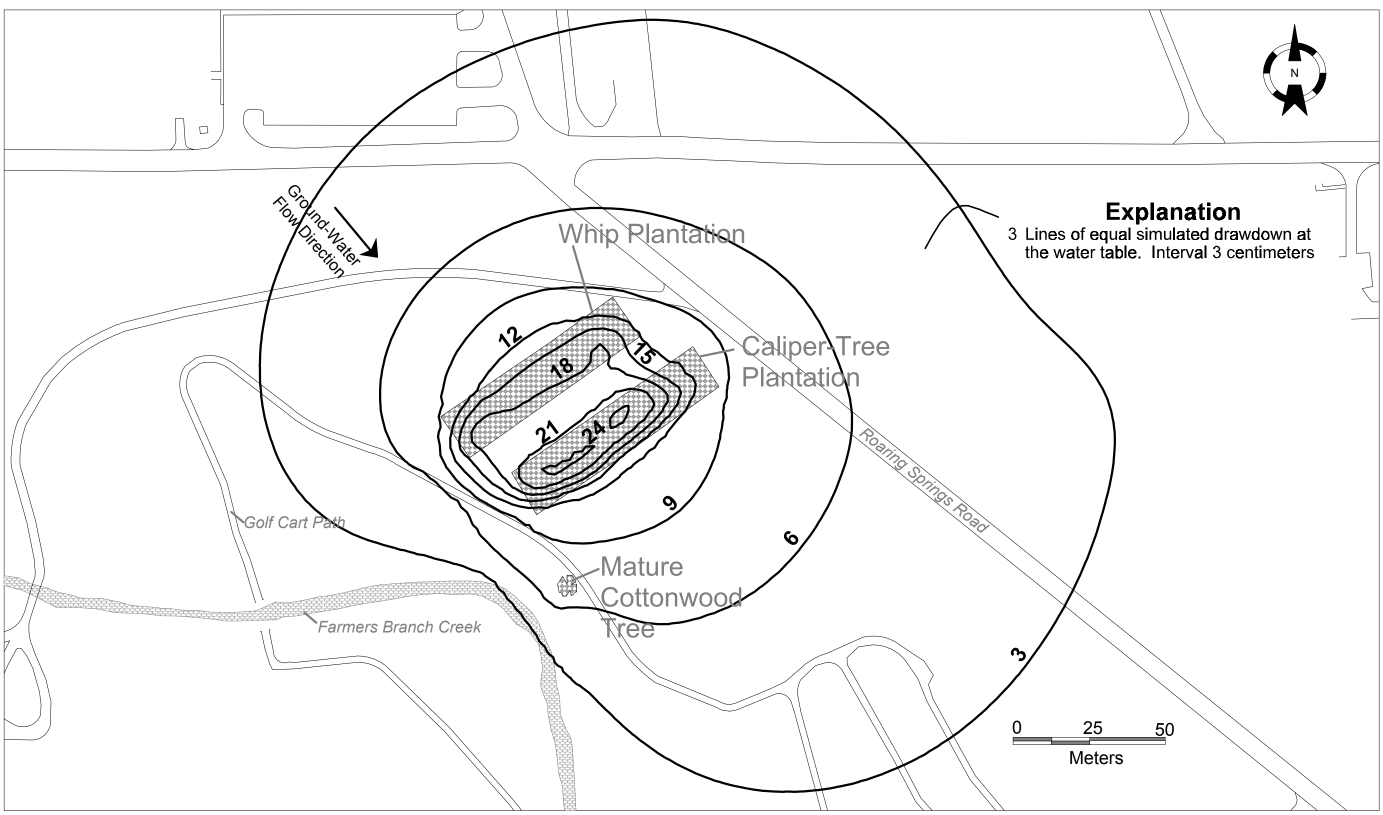

Figure 4-12. Maximum predicted drawdown at the water table for closed-canopy conditions (year 12 and beyond).

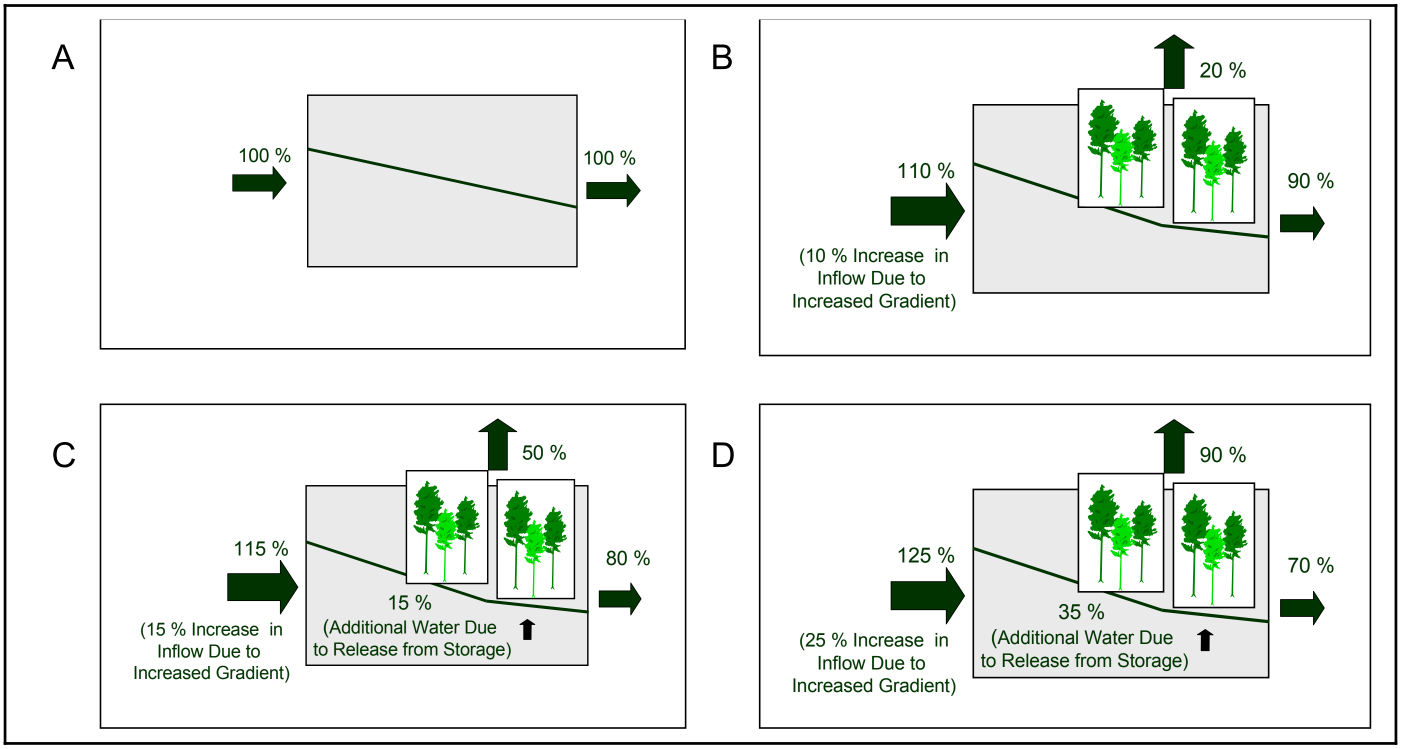

Figure 4-13. Simulated groundwater budget (A) prior to treatment, (B) peak of the third growing season (1998), (C) peak of the growing season once closed canopy has been achieved (year 12 and beyond)–minimum predicted transpiration, and (D) peak of the growing season once closed canopy has been achieved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