

Prepared in cooperation with the U.S. Environmental Protection Agency, Region VII

Assessment of Subsurface Chlorinated Solvent Contamination Using Tree Cores at the Front Street Site and a Former Dry Cleaning Facility at the Riverfront Superfund Site, New Haven, Missouri, 1999–2003



Scientific Investigations Report 2004–5049

Cover Photographs: Tree-core sample in a 40-milliliter vial for headspace analysis (left photo). Collecting a tree-core sample from an oak tree at the Riverfront Superfund Site, New Haven, Missouri, 2000 (right photo).

Assessment of Subsurface Chlorinated Solvent Contamination Using Tree Cores at the Front Street Site and a Former Dry Cleaning Facility at the Riverfront Superfund Site, New Haven, Missouri, 1999–2003

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Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m ²)
acre	0.4047	hectare (ha)
square foot (ft ²)	929.0	square centimeter (cm ²)
square foot (ft ²)	0.09290	square meter (m ²)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
Volume		
gallon (gal)	3.785	liter (L)
cubic inch (in ³)	16.39	cubic centimeter (cm ³)
Flow rate		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
gallon per minute (gal/min)	0.00223	cubic foot per second (ft ³ /s)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Vertical coordinate information is referenced to the “*National Geodetic Vertical Datum of 1929 (NGVD 29).*”

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in soil are given in micrograms per kilogram (µg/kg) and concentrations of chemical constituents in tree-core samples are given as micrograms in head-space per kilogram of wet core (µg-h/kg).

Assessment of Subsurface Chlorinated Solvent Contamination Using Tree Cores at the Front Street Site and a Former Dry Cleaning Facility at the Riverfront Superfund Site, New Haven, Missouri, 1999–2003

By John G. Schumacher¹, Garrett C. Struckhoff¹, and Joel G. Burken²

Abstract

Tree-core sampling has been a reliable and inexpensive tool to quickly assess the presence of shallow (less than about 30 feet deep) tetrachloroethene (PCE) and trichloroethene (TCE) contamination in soils and ground water at the Riverfront Superfund Site. This report presents the results of tree-core sampling that was successfully used to determine the presence and extent of chlorinated solvent contamination at two sites, the Front Street site (operable unit OU1) and the former dry cleaning facility, that are part of the overall Riverfront Superfund Site. Traditional soil and ground-water sampling at these two sites later confirmed the results from the tree-core sampling. Results obtained from the tree-core sampling were used to design and focus subsequent soil and ground-water investigations, resulting in substantial savings in time and site assessment costs.

The Front Street site is a small (less than 1-acre) site located on the Missouri River alluvium in downtown New Haven, Missouri, about 500 feet from the south bank of the Missouri River. Tree-core sampling detected the presence of subsurface PCE contamination at the Front Street site and beneath residential property downgradient from the site. Core samples from trees at the site contained PCE concentrations as large as 3,850 $\mu\text{g-h/kg}$ (micrograms in headspace per kilogram of wet core) and TCE concentrations as large as 249 $\mu\text{g-h/kg}$. Soils at the Front Street site contained PCE concentrations as large as 6,200,000 $\mu\text{g/kg}$ (micrograms per kilogram) and ground-water samples contained PCE concentrations as large as 11,000 $\mu\text{g/L}$ (micrograms per liter). The former dry cleaning facility is located at the base of the upland that forms the south bank of the Missouri River alluvial valley. Tree-core sampling did not indicate the presence of PCE or TCE contamination at the former dry cleaning facility, a finding that was later confirmed by the analyses of soil samples collected from the site.

The lateral extent of PCE contamination in trees was in close agreement with the extent of subsurface PCE contamination determined using traditional soil and ground-water sampling methods. Trees growing in soils containing PCE concentrations of 60 to 5,700 $\mu\text{g/kg}$ or larger or overlying ground water containing PCE concentrations from 5 to 11,000 $\mu\text{g/L}$ generally contained detectable concentrations of PCE. The depth to contaminated ground water was about 20 to 25 feet below the land surface. Significant quantitative relations [probability (p) values of less than 0.05 and correlation coefficient (r^2) values of 0.88 to 0.90] were found between PCE concentrations in trees and subsurface soils between 4 and 16 feet deep. The relation between PCE concentrations in trees and underlying ground water was less apparent (r^2 value of 0.17) and the poor relation is thought to be the result of equilibrium with PCE concentrations in soil and vapor in the unsaturated zone. Based on PCE concentrations detected in trees at the Front Street site and trees growing along contaminated tributaries in other operable units, and from field hydroponic experiments using hybrid poplar cuttings, analysis of tree-core samples appears to be able to detect subsurface PCE contamination in soils at levels of several hundred micrograms per liter or less and PCE concentrations in the range of 8 to 30 $\mu\text{g/L}$ in ground water in direct contact with the roots.

Loss of PCE from tree trunks by diffusion resulted in an exponential decrease in PCE concentrations with increasing height above the land surface in most trees. The rate of loss also appeared to be a function of the size and growth characteristics of the tree as some trees exhibited a linear loss with increasing height. Diffusional loss of PCE in small (0.5-inch diameter) trees was observed to occur at a rate more than 10 times larger than in trees 6.5 inches in diameter. Concentrations of PCE also exhibited directional variability around the tree trunks and concentration differences as large as five-fold were observed around the trunks of several trees. The directional differences were attributable to spatial differences in PCE concentrations in soils around the trees and to natural "twisting" of the tree trunks. The directional differences also may be caused by diffusion of PCE vapors in the unsaturated zone into the tree roots. Compar-

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ison of PCE concentrations in core and sap samples confirms laboratory sorption studies and indicates that the vast majority (greater than 95 percent) of the PCE and TCE reside in the wood phase and not the transpiration stream.

Introduction

The assessment of shallow, subsurface contamination by volatile organic compounds (VOCs) generally has involved the collection of soil, soil-gas, or ground-water samples from boreholes. While advances in drilling, sample collection, and on-site analysis have greatly improved site characterization, the collection of these samples must still be done by invasive methods using equipment that typically requires vehicle access across the site. Unfortunately, cultural features or overgrowth of vegetation limits access to many abandoned or potential waste-disposal sites. In addition, contaminants in ground water may migrate beneath adjacent parcels of land where access for sampling can be limited by local landowners. Recent research has shown that VOCs are present in core samples from trees exposed to contaminated ground water (Burken and Schnoor, 1998; Compton and others, 1998; Vroblesky and others, 1999). Vroblesky and others (1999) demonstrated that trees growing above contaminated shallow ground water at the Savannah River site in South Carolina contained concentrations of trichloroethene (TCE) and *cis*-1,2-dichloroethene (*cis*-DCE) that generally reflected concentrations in a chlorinated solvent plume previously identified by analyses of water samples from monitoring wells and piezometers. In laboratory studies, concentrations of TCE in the transpiration stream of hybrid poplar trees were shown to correlate with TCE concentrations in simulated ground water (Ma and Burken, 2002, 2003).

The available literature suggests that tree-core sampling may be an effective tool for the assessment of subsurface VOC contamination. Tree-core samples have been successfully used to map subsurface contamination by chlorinated solvents and guide the placement of monitoring wells at the Riverfront Superfund Site (U.S. Environmental Protection Agency, 2001). Tree-core sampling, in conjunction with traditional soil and ground-water sampling, was used to map the extent and magnitude of subsurface VOC contamination at several operable units at the Riverfront Superfund Site and to identify several additional areas for future investigation (U.S. Environmental Protection Agency, 2003). Application of tree-core sampling at the Riverfront Superfund Site is unique, in that unlike previous field studies (Vroblesky and others, 1999; Cox, 2002), no subsurface data previously existed at the Riverfront Superfund Site and tree-core sampling was the primary tool used in the initial site assessment.

Background

The Riverfront Superfund Site is located in Franklin County, Missouri, about 40 mi (miles) west of St. Louis, Mis-

souri, in the town of New Haven, Missouri (fig. 1). During routine public water-supply well testing in 1986, the Missouri Department of Natural Resources (MDNR) detected the VOC tetrachloroethene (PCE) in two public water-supply wells (W1 and W2) drilled to more than 800 ft (feet) deep in the northern part of New Haven. Following the discovery of the PCE contamination above the U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) of 5 µg/L (micrograms per liter) for PCE, two new public water-supply wells (W3 and W4) were installed in the southern part of the city, and several investigations of potential sources of the contamination were made by the MDNR and the USEPA during the late 1980's and early 1990's.

The initial investigations of PCE contamination of the public water-supply wells indicated several facilities that were potential sources of the PCE. These facilities included:

- an abandoned manufacturing building in downtown New Haven on Front Street (Front Street site);
- a former dry cleaning facility at the intersection of Wall and Miller Streets;
- a metal fabrication plant (metal plant) in south New Haven on Industrial Drive (Kellwood site);
- a metal finishing plant unit on the east side of the city on East Industrial Drive;
- a fabric plant in the east part of the city on Orchard Street;
- the old city dump on the east side of the city limits; and
- an old (abandoned) hat factory on Wall Street south of public water-supply well W1.

The abandoned manufacturing building in downtown New Haven and former dry cleaning facility were identified as two of the most likely sources of the contamination because they are within 600 ft of the contaminated city wells (fig. 1). In 1998, the USEPA asked the U.S. Geological Survey (USGS) for technical assistance in understanding the geohydrology of the New Haven area and to provide information on the possible directions of ground-water flow and PCE migration from potential sources previously identified. The USGS technical assistance was performed as an Expanded Site Investigation/Remedial Investigation (ESI/RI) that was completed in 2000 (U.S. Environmental Protection Agency, 2001). The ESI/RI included an initial assessment of several sites using tree cores. In December 2000, as a result of the additional data collected during the ESI/RI, the site officially was placed on the National Priorities List (NPL) or "Superfund". The Riverfront Superfund Site currently (2003) has five operable units that include several abandoned and existing manufacturing facilities where PCE was or may have been used and disposed within the city (fig. 1). Core samples collected from hundreds of trees have been used in the characterization of subsurface VOC contamination at the various Remedial Investigation (RI) operable units and along sanitary sewer lines throughout the city. The RI and Feasibility Study (FS) for one of the operable units, the Front Street site,

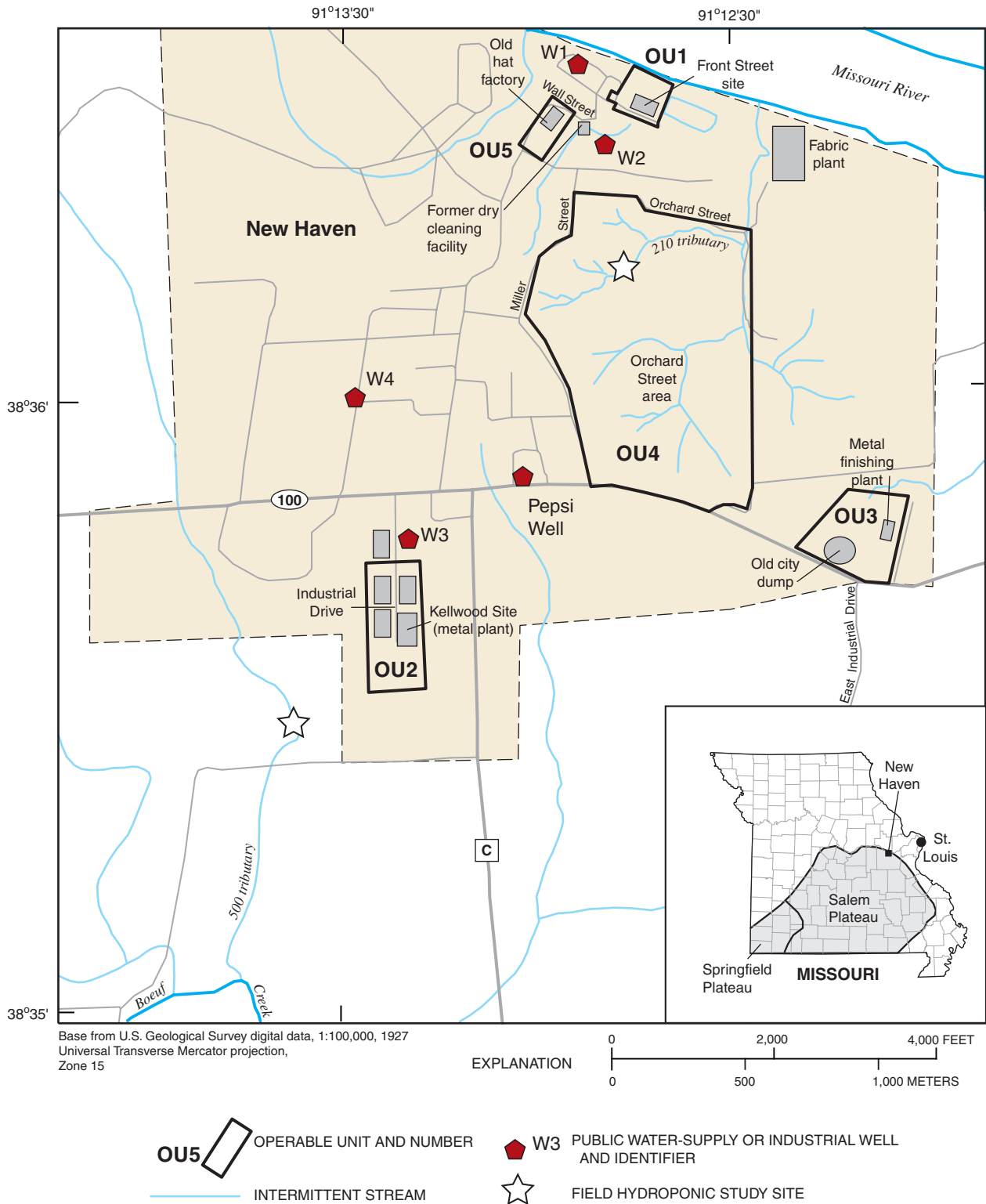


Figure 1. Location of operable units and potential tetrachloroethene (PCE) source areas in relation to contaminated public water-supply wells (W1 and W2) at the Riverfront Superfund Site, New Haven, Missouri.

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were completed in 2003 (U.S. Environmental Protection Agency, 2003; Black and Veatch Special Projects Corporation, 2003). A Record of Decision (ROD) for the Front Street site was prepared by the USEPA in September 2003.

Purpose and Scope

The report describes the assessment of subsurface chlorinated solvent contamination using tree cores at two sites in downtown New Haven, Missouri (Front Street site and the former dry cleaning facility) that were investigated as part of the Riverfront Superfund Site. During an initial assessment in 1999, core samples were collected from 32 trees in the downtown area. Results from these samples were used to scope and design the subsurface characterization of soils and a ground-water monitoring network at what would become RI operable unit OU1 (Front Street site). The former dry cleaning facility is within several hundred feet of OU1 and was investigated as part of the OU1 investigation. During the RI, which began in 2000, hundreds of soil and dozens of ground-water samples were collected to characterize the extent and magnitude of contamination at these two sites. Additional tree-core samples also were collected during the RI to better understand the relations between chlorinated solvent concentration in trees and the subsurface. As of May 2003, more than 70 trees have been sampled in the vicinity of the Front Street site and the former dry cleaning facility. Data from tree-core sampling were compared to more traditional site characterization data, such as data from soil borings and monitoring wells, to demonstrate that the initial assessment using tree cores was a reliable indicator of the presence or absence of subsurface VOC contamination at these two sites. Relations between concentrations of VOCs in tree cores, soil, and ground water are presented along with data suggesting that concentrations of VOCs in the tree-core samples are dependent upon the VOC concentrations in the subsurface, depth to ground water, collection height, tree size and species, and directional location around the tree trunk. Practical considerations and possible limitations on the use of tree coring in site assessment based on experiences at the Riverfront Superfund Site also are presented.

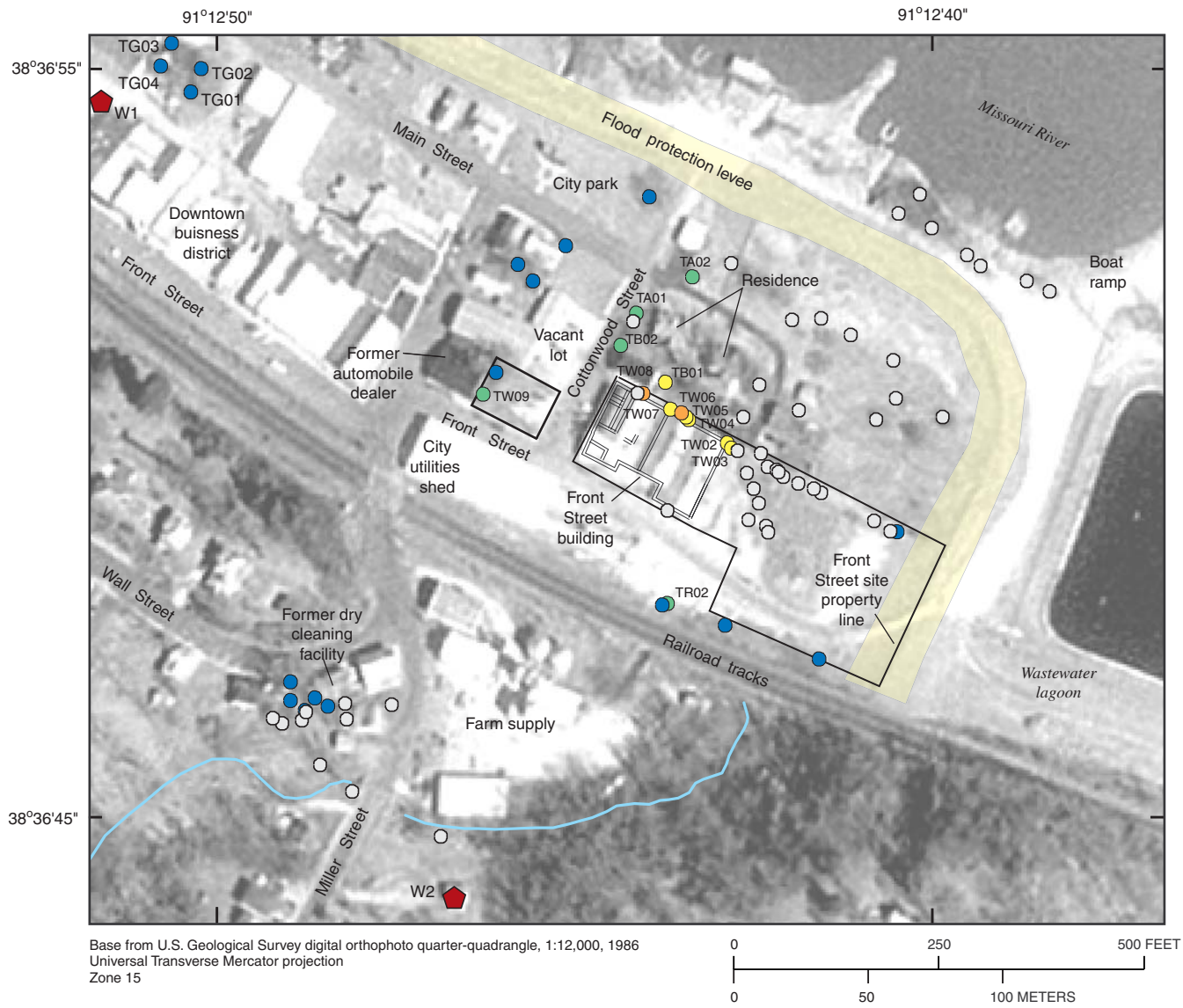
Description of the Study Area

The Front Street site is on the northwest corner of the intersection of Front Street and Cottonwood Street in downtown New Haven (fig. 2). The site consists of a vacant 15,000 ft² (square foot), one-story building (Front Street building) situated on a 1.5-acre lot east of Cottonwood Street, and a 0.1-acre vacant lot on the west side of Cottonwood Street (fig. 2). The building lot is level with less than 1.5 ft of relief. Front Street provides access to a boat ramp on the Missouri River about 500 ft northeast of the site and to the city wastewater lagoon east of the site. The Front Street site is behind a flood protection levee designed and built by the U.S. Army Corps of Engineers (USACE) that surrounds downtown New Haven (fig. 2).

Several industries have operated at the site since the 1950's and the Front Street building was built in at least five phases. The initial part of the building was built in the late 1940's and operated as a local "machine shop". In the early 1950's, a major manufacturer of tents and outdoor products moved several production facilities into New Haven. From the early 1950's through 1972, the machine shop was contracted to manufacture and finish aluminum tent poles and stakes and several additions were made to the building to accommodate the increased business. The process included cleaning the poles with PCE. After 1972, several other industries operated for short periods at the facility, including a hospital bed manufacturer, a truck spring plant, a golf cart supplier, and an automobile repair shop.

The Front Street site is located on the Missouri River flood plain about 400 ft from the south bank of the river, and is underlain by between 20 and 35 ft of alluvial sediments. The surface of the alluvium is gently sloping and ranges from an altitude of about 501 ft near the railroad tracks south of the building to about 490 ft at the boat ramp northeast of the site (fig. 2). The edge of the alluvium is immediately south of the railroad tracks, and its thickness increases toward the Missouri River where it is more than 50 ft thick. The stratigraphy of the alluvium at OU1 is relatively homogeneous, consisting mostly of silt and silty-loam from 0 to about 20 ft deep, grading into fine- and coarse-grained sands deeper than 20 to 25 ft (U.S. Environmental Protection Agency, 2003). Ground water in the alluvium beneath the site averages about 20 to 25 ft below the land surface. During periods of flooding, water levels rise to within 10 ft below the land surface, and may be shallower during prolonged periods of flooding such as occurred during 1993 and 1995. At normal river stages, ground-water flow in the alluvium beneath the site is northeast toward the Missouri River. However, during periods of high river stages, a trough develops in the alluvial water table just northeast of the site and parallel to the river (fig. 3).

The former dry cleaning facility is located near the intersection of Wall Street and Miller Street near the base of the upland slope composing the south boundary of the Missouri River valley (fig. 2). The site is in a residential area and is about 300 ft from the contaminated city well W2. From the late 1950's through the early 1970's, dry cleaning was done in the basement of what is now a residence situated on a small (less than 0.2 acre) lot on the south side of Wall Street (U.S. Environmental Protection Agency, 2003). The lot slopes steeply from Wall Street to the south property line, which borders the back yard of an adjacent residence. Access to the site is restricted because of the high density of homes and steep slopes. The site is underlain by a mixture of loess and colluvium. City utility workers indicate that bedrock beneath Wall Street north of the former dry cleaning facility is less than 7 ft deep. A small intermittent creek, which drains about 0.1 mi² (square mile) of residential area to the south, is about 100 ft south of the former dry cleaning facility. The creek flows beneath Miller Street north of city well W2 and enters a concrete storm drain near the railroad tracks.



EXPLANATION

- TR02 TREE-CORE SAMPLE AND IDENTIFIER
- AVERAGE TETRACHLOROETHENE (PCE) CONCENTRATION IN TREE-CORE SAMPLE—Concentration in micrograms in headspace per kilogram of wet core
 - Not sampled during 1999
 - Not detected
 - 0.1 to 4.9
 - 5.0 to 49.9
 - 50 to 162
- INTERMITTENT STREAM
- W2 ■ PUBLIC WATER-SUPPLY WELL AND IDENTIFIER

Figure 2. Results of initial tree-core sampling conducted in downtown New Haven, Missouri, during 1999.

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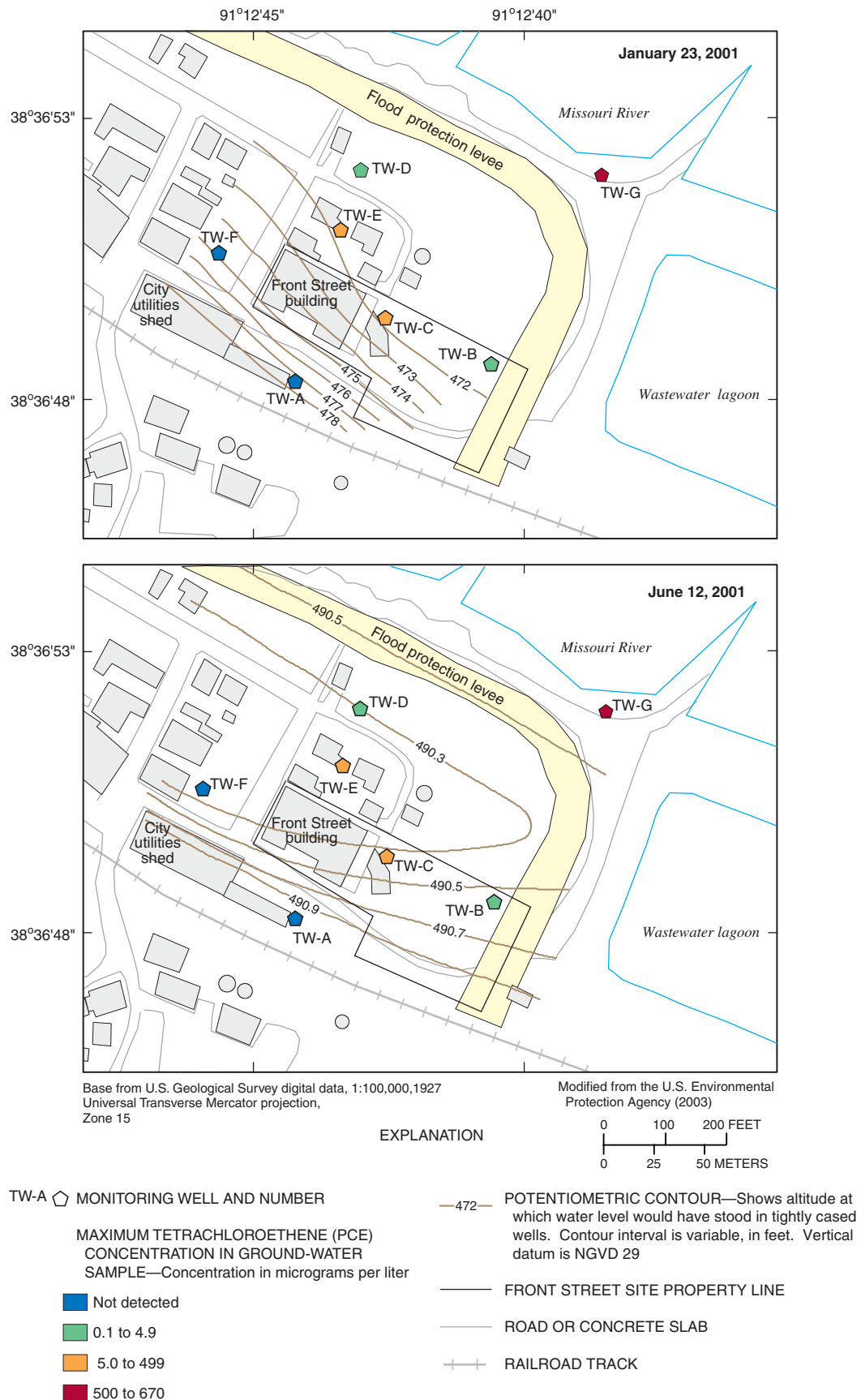


Figure 3. Ground-water flow in the Missouri River alluvium at the Front Street site during normal stage (January 23, 2001) and high stage (June 12, 2001) of the Missouri River.

Sample Collection and Analysis

Core samples generally were collected from trees with diameters of 3 in. (inches) or larger. If multiple species were present at a single location, preference was given to species that are known to grow rapidly and have deep root systems, such as mulberry, poplar, and cottonwood. A 0.169- by 6-in. long increment borer was used to collect the core samples. During the initial assessment in 1999, composite samples from trees were prepared by collecting two cores from opposite sides of each tree about 3 ft above the land surface. Only one core was collected from trees smaller than about 6-in. diameter. Cores from each tree were placed in a single pre-weighed 40-mL (milliliter) standard VOC vial fitted with a Teflon-lined septum cap. Cores were collected as quickly as possible to minimize volatilization loss. Typically, cores from a single tree were collected within one minute and the vial was capped immediately after the collection of each core. At least one core sample was collected from the side facing the suspected contaminated area. For example, trees on the north side of the Front Street building were initially cored on the south side, then on the north side depending on the diameter of the tree. Trees along the railroad tracks initially were cored on the south side, then on the north side depending on their diameter. Cores collected from trees at the former dry cleaning facility were collected from opposite sides of each tree, but at no specified side because the suspected area of dumping, if any occurred, was not known at that time. Because of concerns about PCE volatilization from the vial when adding the second core, after 1999, only single cores were collected from each tree.

After collection, vials were returned to the USGS laboratory in Rolla, Missouri, and allowed to equilibrate overnight at room temperature to allow PCE and other VOCs to diffuse from the cores into the headspace in the vial. A 250- μ L (microliter) sample of the headspace in the vials was collected using a glass syringe. The samples were analyzed using a Photovac 10S Plus gas chromatograph (GC) equipped with a photoionization detector. Chromatographic separation was performed isothermally at 40 °C (degrees Celsius) for 500 seconds with a CPSIL-5 capillary column with an air flow rate of 10.5 mL/min (milliliters per minute). Standards were prepared daily by placing 5 μ L of a methanol-based standard solution containing certified quantities of PCE, TCE, cis-DCE, benzene, and toluene into a 40 mL septum-capped vial containing 20 mL of organic-free distilled water. The stock standard solution was obtained from Supelco in sealed glass ampules and stored at -20 °C until use. Samples containing concentrations of individual VOCs larger than 50 μ g/L were rerun and diluted by injecting a smaller quantity of sample collected from the headspace of the vial.

Concentrations of PCE and other VOCs in tree cores initially were expressed as micrograms of VOC per kilogram of wet core (U.S. Environmental Protection Agency, 2001, 2003). This was done assuming that the partitioning of PCE and other VOCs between the headspace and core was similar to that between air and water. Recent research has provided partitioning coefficients between air/wood and wood/water for TCE and

PCE (Ma and Burken, 2002, 2003; Struckhoff, 2003) and concentrations expressed in this report have been adjusted and reported as mass (micrograms) of VOC in the headspace per kilogram of wet core (μ g-h/kg). This unit of measure was chosen because it is a compromise between the inherent inaccuracy of reporting only headspace concentration and the more accurate approach of reporting wood and transpiration stream concentrations using partitioning coefficients between water, wood, and air. A limitation of using partitioning coefficients to determine the fractions of VOCs in wood, water, and air is that it is necessary to determine partitioning coefficients for every compound in every type of plant material being sampled. Recently published values of partitioning coefficients of PCE into poplar trees indicate that about 95 percent of the PCE is sorbed into the wood while only about 5 percent is present in the water phase (Struckhoff, 2003). Because the majority of PCE in the core resides in the wood phase, the headspace concentrations in this report were normalized to the total core mass, rather than to the core water mass. By normalizing to total core mass, all that is required is to multiply the headspace concentration by the headspace volume and divide by the total core mass.

There are some limitations associated with expressing concentrations as micrograms in headspace per mass of core. First, the headspace in the vial (empty vial less volume of core) containing the core must be known. The volume of core often is calculated using an assumed density of the tree core. In this report, the core density was assumed to be 1.0 g/cm³ (gram per cubic centimeter). Actual densities of trees cored in the New Haven area probably are in the range of 0.5 to 0.9 g/cm³ reported for cedar, maple, and oak (CRC Press Inc., 1989). Because of the generally small volume of core to total vial volume, the error in reported VOC concentration introduced by assuming the core density of 1.0 is less than 5 percent. Second, in cases where composite samples of multiple cores are placed in the same vial, there can be significant loss of the contaminant in the few seconds while the vial lid is open. This can be understood by considering that Henry's Law indicates that about 40 percent of PCE goes into the headspace and the observation that when a core is placed into a vial and capped, condensation usually can be seen almost immediately on the inside of the glass. The rapid formation of condensation indicates a rapid loss of water, and probably VOCs, from the core, and demonstrates that the vials must be capped as quickly as possible. Another limitation in headspace analysis is variability between different sampling procedures such as the use of different sized vials. If two cores of the same size are placed into different sized vials, measured VOC concentrations will be different when reported as micrograms in headspace per kilogram of wet core. Therefore, the size of cores in proportion to the vial size should remain approximately the same during field sampling efforts or results will not be directly comparable.

Assessment of Subsurface Contamination at the Front Street Site

Through interviews with local residents and former employees of the relevant facilities, the USEPA determined that PCE was used and probably disposed at the Front Street site during the 1950's and 1960's. However, specific information regarding the quantities of PCE used and manner and location of disposal at the site was not known. Because the site is near a USACE-sponsored flood protection levee, stringent limitations exist on the installation of subsurface borings and monitoring wells to protect the stability of the levee foundation. In addition to limitations on subsurface boring and drilling, the property north and northeast of the Front Street building is residential and under private ownership. Because of the restrictions on subsurface boring and the occasional reluctance of some residential property owners to grant access for drill rigs, the site was a good candidate for an initial reconnaissance using tree-coring methods.

Initial Site Assessment Using Tree Cores

The initial tree-core sampling at the Front Street site was conducted during July and August 1999. Trees were selected based on their proximity to the Front Street building. Several trees were cored again during October 1999 to serve as positive controls for the initial assessment of the former dry cleaning facility. PCE was detected in 13 of the 26 trees cored in the downtown area (fig. 2). Concentrations of PCE detected ranged from a trace concentration of 0.32 $\mu\text{g-h/kg}$ (microgram in headspace per kilogram of wet core) in a hackberry tree (TW09) west of the site to 162 $\mu\text{g-h/kg}$ in a mulberry tree (TW08) on the north side of the building (table 1). Except for the trace PCE concentrations (less than 1.0 $\mu\text{g-h/kg}$) in trees TW09 and TA02, all PCE detections were in trees along the north side of the building or on residential property north of the site.

TCE was detected in only five trees and at concentrations less than 5.0 $\mu\text{g-h/kg}$ (table 1). The largest TCE concentration detected was 3.14 $\mu\text{g-h/kg}$ in tree TW08. Concentrations of TCE generally were positively correlated with PCE concentrations. Four background trees (TG01, TG02, TG03, and TG04) were sampled in the western part of the downtown area to serve as negative controls (fig. 2). None of the background trees contained PCE or TCE, but three of the four did contain detectable concentrations of toluene (1.32 to 4.44 $\mu\text{g-h/kg}$) or benzene (7.47 $\mu\text{g-h/kg}$). Toluene also was detected in samples from trees TW01 and TW02 (0.39 and 1.33 $\mu\text{g-h/kg}$). There was an automobile dealership, a bulk fuel depot, and several former gasoline service stations in downtown New Haven, and several old underground fuel tanks were identified during the RI (U.S. Environmental Protection Agency, 2003). Leaks or spills at these facilities may be a source of the small concentrations of benzene and toluene detected in some trees. Several trees also contained small concentrations of what appeared to be cis-

DCE; however, core samples from negative control trees in a remote national forest contained small (few micrograms in headspace per kilogram of wet core) concentrations of a compound with a similar retention time to cis-DCE; therefore, concentrations of cis-DCE less than 10 $\mu\text{g-h/kg}$ are considered unreliable.

Considerable variability (52 to 55 percent difference) was present in replicate core samples collected from trees TW02 and TW08 with the replicate sample being smaller. This variability is probably caused by differences in sampling technique as the replicate cores were placed in vials that contained 5 mL of organic-free water and were stored in an inverted position before analysis. The water was added to reduce the potential for diffusive loss of VOCs through the septa of the vials. Rather than preventing VOC loss, the addition of water appeared to enhance VOC loss because the replicate samples contained up to 55 percent less PCE than the original sample. The smaller concentrations in the replicate samples probably result from a combination of PCE partitioning into the water phase and slightly longer time required to avoid spilling water from the vials while adding the core samples. The addition of water to replicate vials was not done after August 1999.

Based on the results of the initial tree-core sampling, the USEPA determined that PCE contamination was present at the Front Street site and that additional investigation of the site was warranted. The absence of significant PCE concentrations in trees south and west of the Front Street building was interpreted to mean that potential spills along the railroad tracks or at the old automobile dealership (west of the site) probably were not the source of PCE contamination. Based on the presumed direction of ground-water flow in the alluvium beneath the site (north-northeast toward the Missouri River) and the large concentrations of PCE in trees along the north side of the building, a conceptual model of PCE contamination at the site was developed (U.S. Environmental Protection Agency, 2003). This conceptual model was that PCE was disposed at or in the immediate vicinity of the Front Street building and that a plume of PCE contaminated ground water was moving beneath the private property north of the site and discharging into the Missouri River.

Comparison of Tree-Core Sampling to Traditional Soil and Ground-Water Sampling at the Front Street Site

During the RI of the Front Street site, an additional 39 trees near the site were sampled (U.S. Environmental Protection Agency, 2003). These trees were sampled as part of a larger effort to characterize the extent and magnitude of subsurface contamination at the site, which included the collection of subsurface soil samples from more than 140 locations, and ground-water samples from 7 monitoring wells and 21 temporary drive point locations in the alluvial aquifer near the site (U.S. Environmental Protection Agency, 2003). During the RI, tree-core samples generally were collected contemporaneously with soil and ground-water samples. However, in the case of a private

Table 1. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from downtown New Haven, Missouri, during 1999

[All concentrations in micrograms per liter in headspace per kilogram of wet core; Rep, replicate; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; t-DCE, trans-1,2-dichloroethene; --, no data; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit]

Tree identifier	Date	Time	Rep	PCE	TCE	cis-DCE	t-DCE	Benzene	Toluene	Description
Trees sampled near the Front Street building or downtown area										
TA01	08/11/99	--	--	1.38	<0.8	<10	<0.8	<0.8	<0.8	10 in. Hard maple
TA02	08/11/99	--	--	.58 J	<.8	<10	<.8	<.8	<.8	10 in. Birch, 3 trunks
TB01	08/11/99	--	--	35.7	.77 J	<10	<.8	<.8	<.8	11 in. Walnut
TB02	07/13/99	1236	--	.93	<.8	<10	<.8	<.8	<.8	20 in. Silver maple
	08/11/99	--	--	.99	<.8	<10	<.8	<.8	<.8	20 in. Silver maple
TG01	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	1.32	34 in. Chinese elm
TG02	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	2.66	34 in. Chinese elm
TG03	08/11/99	--	--	<.8	<.8	<10	<.8	7.47	4.44	36 in. Chinese elm
TG04	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	34 in. Silver maple
TM01	08/20/99	--	--	<.8	<.8	.64	<.8	<.8	<.8	30 in. Boxelder
TM02	08/20/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	38 in. Silver maple
TM03	08/20/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	12 in. Hard maple
TR01	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	7 in. Hackberry
TR02	08/11/99	--	--	.57 J	<.8	<10	<.8	<.8	<.8	6 in. Chinese elm
TR03	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	4 in. Hackberry, 3 trunks
TR04	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	4 in. Hackberry
TW01	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	.39 J	11 in. Mulberry
TW02	08/11/99	--	--	37.1	<.8	<10	<.8	<.8	1.33	10 in. Eastern red cedar
	10/22/99	1719	--	53.2	<.8	.21 J	<.8	<.8	2.38	10 in. Eastern red cedar
	10/22/99	1719	R	24.1	<.8	.56 J	<.8	<.8	<.8	10 in. Eastern red cedar
TW03	08/11/99	--	--	9.93	<.8	2.05 J	<.8	1.45	<.8	6 in. Chinese elm
	10/22/99	1719	--	9.94	<.8	1.41 J	<.8	<.8	<.8	6 in. Chinese elm
TW04	08/11/99	--	--	47.6	.10	<10	<.8	.04 J	<.8	3 in. Mulberry, 2 trunks
TW05	08/11/99	--	--	34.5	<.8	<10	<.8	<.8	<.8	4 in. Mulberry
TW06	08/11/99	--	--	75.9	1.85	<10	<.8	.48 J	<.8	3 in. Mulberry
TW07	08/11/99	--	--	41.1	1.37	<10	<.8	<.8	<.8	10 in. Cottonwood
TW08	07/13/99	1226	--	84.0	.42 J	<10	<.8	<.8	<.8	8 in. Mulberry
	07/13/99	1226	R	55.4	.17 J	<10	<.8	<.8	<.8	8 in. Mulberry
	08/11/99	--	--	162	3.14	2.58 J	<.8	.37 J	<.8	8 in. Mulberry
TW09	08/11/99	--	--	.32 J	<.8	<10	<.8	.05 J	<.8	20 in. Hackberry
TW10	08/11/99	--	--	<.8	<.8	<10	<.8	.12 J	<.8	3 in. Chinese elm

Table 1. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from downtown New Haven, Missouri, during 1999—Continued

[All concentrations in micrograms per liter in headspace per kilogram of wet core; Rep, replicate; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; t-DCE, trans-1,2-dichloroethene; --, no data; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit]

Tree identifier	Date	Time	Rep	PCE	TCE	cis-DCE	t-DCE	Benzene	Toluene	Description
Trees sampled near the former dry cleaning facility										
DF-1	10/20/99	1125	--	<0.8	<0.8	0.48 J	<0.8	<0.8	<0.8	36 in. Chinese elm, east side
DF-1	10/21/99	1125	R	<.8	<.8	.41 J	<.8	<.8	<.8	36 in. Chinese elm, west side
DF-1	10/20/99	1140	--	<.8	<.8	7.61 J	<.8	<.8	<.8	36 in. Chinese elm, west side
DF-2	10/20/99	1130	--	<.8	<.8	1.07 J	<.8	<.8	<.8	30 in. Silver maple, west side
DF-2	10/21/99	1130	--	<.8	<.8	.95 J	<.8	<.8	<.8	30 in. Silver maple, east side
DF-3	10/20/99	1135	--	<.8	<.8	<10	<.8	<.8	<.8	30 in. Silver maple, east side
DF-3	10/20/99	1135	--	<.8	<.8	<10	<.8	<.8	<.8	30 in. Silver maple, west side
HS-1 ^a	09/09/99	1615	--	<.8	<.8	<10	<.8	<.8	<.8	34 in. Chinese elm, south side
HS-2 ^a	09/09/99	1615	--	<.8	<.8	<10	<.8	<.8	<.8	10 in. Mulberry, 2 trunks, south side
HS-3 ^a	09/09/99	1625	--	<.8	<.8	<10	<.8	<.8	<.8	20 in. Hackberry, south side
HS-4 ^a	09/09/99	1630	--	<.8	<.8	<10	<.8	<.8	<.8	20 in. Chinese elm, south side
HS-5 ^a	09/09/99	1635	--	<.8	<.8	<10	<.8	<.8	<.8	22 in. Redbud, south side
T201	07/13/99	1216	--	<.8	<.8	<10	<.8	<.8	<.8	34 in. Silver maple, north side
T201	07/13/99	1216	R	<.8	<.8	<10	<.8	<.8	<.8	34 in. Silver maple, north side
T202	08/11/99	--	--	<.8	<.8	<10	<.8	<.8	<.8	12 in. Chinese elm, north side
Count	32			16	4	1	<10	2	5	
Minimum detected concentration				0.93	0.10	0.64	<10	1.45	1.32	
Maximum detected concentration				161.92	3.14	0.64	<10	7.47	4.44	
Average detected concentration				42.10	1.61	0.64	<10	4.46	2.43	

residence between the site and the Missouri River, permission was given for the collection of tree-core samples in 2001, but permission for soil and ground-water sampling was not obtained until 2003. Results of tree-core sample analysis from this parcel were used to select locations for the collection of soil and ground-water samples.

Results of the tree-core sampling during the ESI/RI and RI indicate subsurface PCE contamination on the south and north sides of the Front Street building, and in an area extending from the building to the Missouri River (fig. 4). The area of contamination was estimated to be about 600 ft long and 200 to 300 ft wide. The largest PCE concentrations (370 to 3,850 $\mu\text{g-h/kg}$) detected within this area were in tree TW11 (a 6-in. diameter Chinese elm) adjacent to the south side of the building. Large PCE concentrations also were detected along the north side of the building in trees TW02 (35.4 to 1,017 $\mu\text{g-h/kg}$), TW06 (27.2 to 1,410 $\mu\text{g-h/kg}$), and TW28 (146 to 1,090 $\mu\text{g-h/kg}$). The core sample from tree JS77, located on the private parcel between the Front Street building and the Missouri River, also contained a large PCE concentration (717 $\mu\text{g-h/kg}$).

Comparison of Tree-Core Sampling to Traditional Soil Sampling Methods

Results of the soil investigation indicated substantial PCE contamination at the site with PCE detected at 128 of the 144 soil locations sampled (U.S. Environmental Protection Agency, 2003). The soil samples were collected from a combination of soil borings made during the RI and from borings and excavations made during a 2000 USEPA emergency removal action to replace a contaminated municipal water-supply line and associated soils beneath Front Street (fig. 4). Soil samples from boreholes generally were collected every 2 ft in depth and most boreholes extended to the base of the alluvium (about 28 to 32 ft deep beneath the site). The largest PCE concentrations [as large as 6,200,000 $\mu\text{g/kg}$ (micrograms per kilogram)] were detected beneath the southeastern part of the Front Street building and along Front Street (fig. 4). In general, PCE concentrations and the lateral extent of PCE contaminated soils increased with increasing depth and reached a maximum at the 14- to 16-ft depth interval.

Concentrations of PCE in trees appear to be a good indicator of PCE concentrations in subsurface soils. In general, PCE was detected in trees growing in areas where soil samples from less than 16 ft deep contained PCE concentrations greater than 60 $\mu\text{g/kg}$, whereas trees growing outside of these areas generally contained little or no detectable PCE (fig. 4). A quantitative relation between PCE concentrations in tree-core samples and soil samples also was observed. Regression analyses indicate a statistically significant (probability values, p , less than 0.05) positive correlation between PCE concentrations in tree-core samples and soil samples collected from 4, 6, 8, 10, 12, and 16 ft below the surface (fig. 5). Concentrations were converted to logarithms (base 10) because PCE concentrations in soil spanned more than 7 orders of magnitude, and PCE concentra-

tions in tree cores spanned more than 4 orders of magnitude. Results of the regression analyses for each depth were similar with correlation coefficient (r^2) values ranging from 0.88 to 0.90. The best fit (r^2 of 0.90) was a linear equation obtained between PCE concentrations in trees and soils at 12 ft deep:

$$\log[\text{PCE in tree } (\mu\text{g-h/kg})] = 0.598 * \log[\text{PCE in soil } (\mu\text{g/kg}) \text{ at 12 ft deep}]$$

The regression constants were not significantly different from zero (p values much larger than 0.05). The similar r^2 values for the various depths probably are related to the correlation between PCE concentrations at various depths. In most locations where trees were cored, soil samples collected from between 4 to 16 ft deep had PCE concentrations of similar magnitudes.

Soil samples generally were collected for the purpose of mapping the extent of subsurface PCE contamination, and not for the expressed purpose of defining the relation between PCE concentrations in the tree and adjacent soil. Therefore, soil borings were not always located near each tree sampled and PCE concentrations in soil beneath each tree were estimated as a weighted average of PCE concentrations from the nearest three soil sample locations (in some cases several tens of feet from the sampled tree). However, soil borings were made adjacent to trees containing the largest PCE concentrations (TW02, TW06, TW08, TW11, and TW28).

The strong relation between PCE in trees and soil samples at the site may be related to PCE being sorbed to soils during periods of high ground-water levels and the probable shallow tree root depth compared to the average depth to ground water. During periods of high Missouri River stage, contaminated ground water that normally is 20 to 25 ft beneath the land surface rises to within 10 ft or less of the land surface, and PCE is sorbed to soils in what normally is the unsaturated zone. This mechanism explains the detection of PCE in soils above the water table outside of areas along Front Street where it was disposed (fig. 4) such as on the residential property between the site and the Missouri River (U.S. Environmental Protection Agency, 2003). For example, PCE concentrations in soil samples from the residential property gradually increased from below detection at the surface to a maximum of 180 $\mu\text{g/kg}$ at depths of about 16 ft (probable top of the capillary fringe under normal river stages), then increase steadily to as large as 2,780 $\mu\text{g/kg}$ at depths below 25 ft (U.S. Environmental Protection Agency, 2003). Trees at the Front Street site are not flood-tolerant species and their root systems likely will not develop in the permanently saturated, oxygen limited (iron to sulfate reducing conditions) soils that exist beneath about 20 ft deep. Runoff from the site is restricted because of the flood protection levee, and the soils are silty-loams that have high infiltration rates leading to sufficient soil moisture contents (20 to 25 percent by weight) for tree growth throughout the year at depths below about 6 ft (U.S. Environmental Protection Agency, 2003). Because of the sufficient supply of soil moisture, root systems in trees at the Front Street site probably develop at

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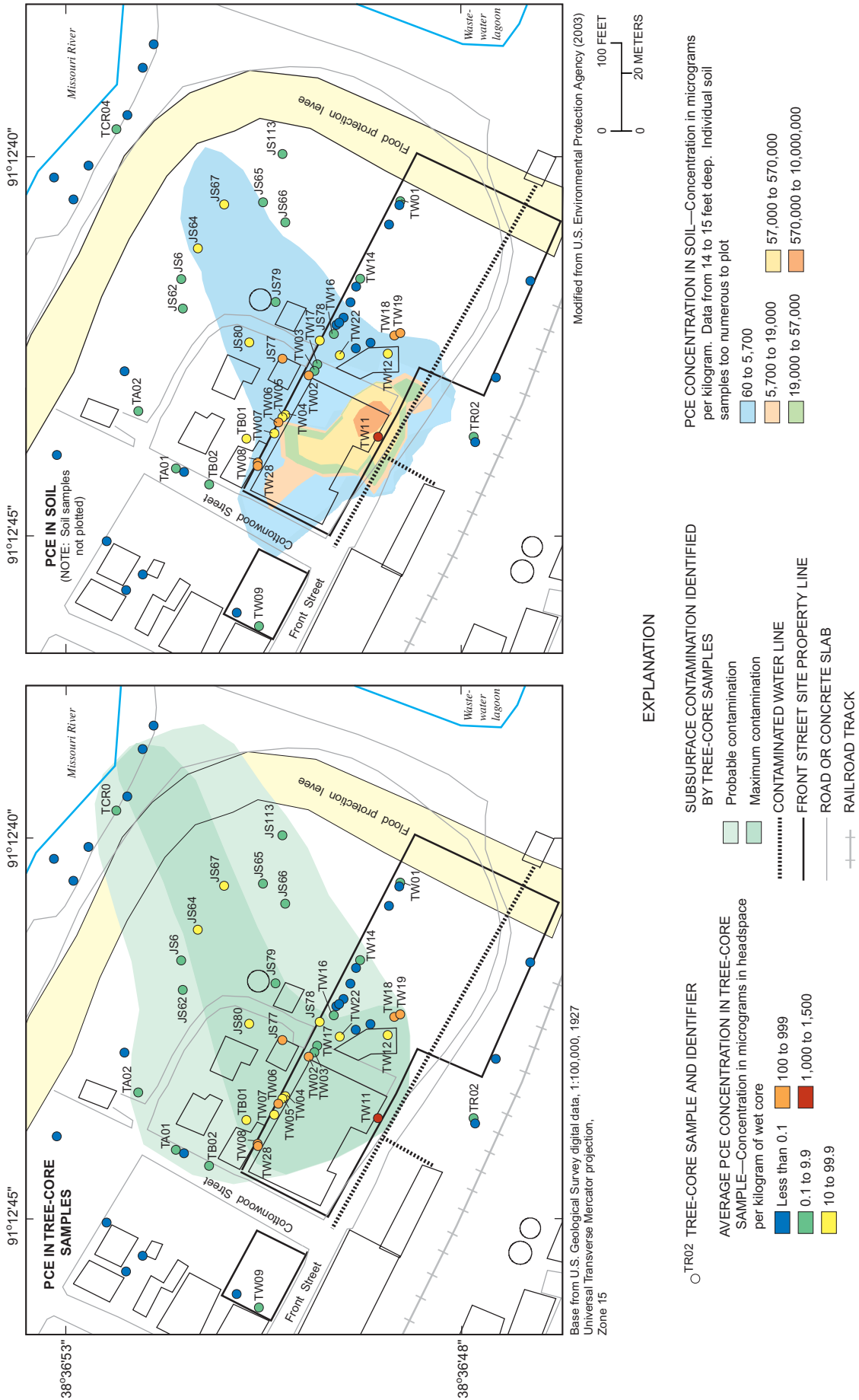


Figure 4. Relation between average tetrachloroethene (PCE) concentrations in tree-core samples and PCE concentrations in soil at the Front Street site (1999–2003).

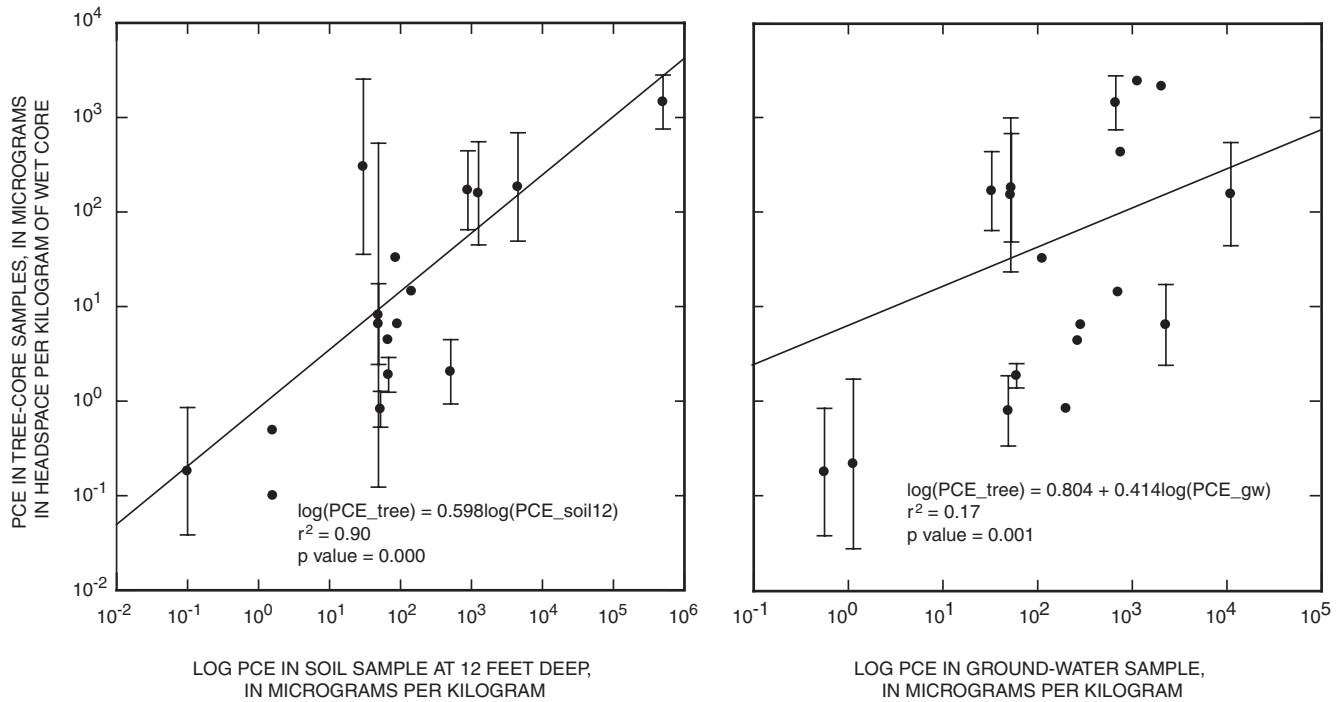


Figure 5. Relation between tetrachloroethene (PCE) concentrations in tree-core samples to PCE concentrations in soil and ground-water samples from the Front Street site.

depths less than about 10 to 12 ft. The suspected shallow root depths as compared to the average depth to ground water (20 to 25 ft deep) is an important factor contributing to the strong relation between PCE in trees and soil at the site.

The strong relation between PCE concentrations in trees and soil at this site has important implications for the use of tree cores in mapping subsurface contamination by chlorinated solvents. Although Vroblesky and others (1999) first demonstrated that trees growing above a known plume of shallow (less than 5 ft deep) contaminated ground water can uptake chlorinated solvents, results from the Front Street site indicate that where depths to contaminated ground water are deeper (20 to 25 ft), VOC concentrations in the soil or unsaturated zone may have more affect on the VOC concentrations detected in trees.

Comparison of Tree-Core Sampling to Ground-Water Sampling

Ground-water samples collected from a network of 7 monitoring wells and 21 temporary direct-push well screen locations during 1999–2003 indicate that a plume of PCE contaminated ground water extends from Front Street south of the Front Street building northeast to the Missouri River (fig. 6). The plume is about 600 ft long and less than 300 ft wide. The areal extent of the PCE plume defined by ground-water sample analyses is of similar size and shape to the subsurface plume esti-

ated using the tree-core data (fig. 4). The core of the ground-water plume, which contains PCE concentrations between 500 and 11,000 $\mu\text{g/L}$, is less than 100 ft wide (fig. 6). The largest PCE concentrations were detected in ground-water samples from beneath the east part of the Front Street building at temporary well screen locations G67 (11,000 $\mu\text{g/L}$), G50 (6,600 $\mu\text{g/L}$), and G51 (6,100 $\mu\text{g/L}$). Large PCE concentrations also were detected about 500 ft downgradient (northeast) from the building near the boat ramp in samples from monitoring well TW-G (less than 1 to 670 $\mu\text{g/L}$) and temporary well screen locations GP22 (less than 130 to 1,100 $\mu\text{g/L}$) and GP28 (5.9 to 340 $\mu\text{g/L}$). PCE was not detected upgradient (south) from the site in monitoring well TW-A or west of the site in monitoring well TW-F.

A qualitative relation also exists between the detection of PCE in tree cores and the presence of PCE in ground water at the Front Street site. Trees overlying the ground-water PCE plume generally contained detectable concentrations of PCE, whereas trees outside the area of PCE contaminated ground water generally did not contain detectable concentrations of PCE (fig. 6). However, in contrast to the strong quantitative relation between PCE concentrations in tree cores and soil, the relation between PCE concentrations in trees and underlying ground water was less apparent (fig. 5). Regression analyses indicated a poor relation (r^2 of 0.17) between PCE concentrations in tree cores and PCE concentrations in the underlying ground water. The regression constant was significantly different from zero (p value of 0.012) and was included in the regres-

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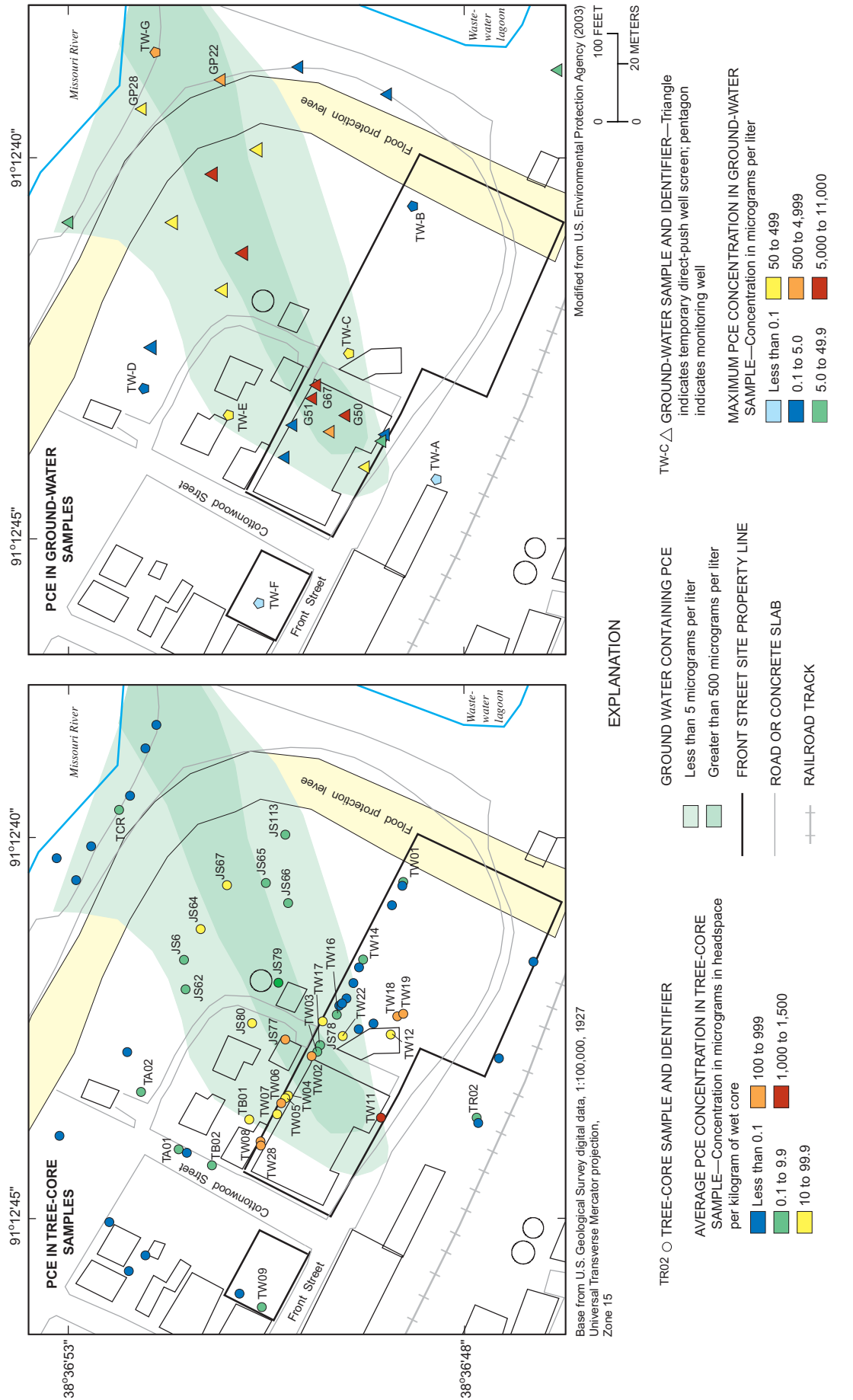


Figure 6. Relation between average tetrachloroethene (PCE) concentrations in tree-core samples and PCE concentrations in ground-water samples at the Front Street site (1999–2003).

sion. This poor relation is in contrast to previous work that has shown direct relations between concentrations of TCE in trees and ground water or bulk solution concentrations in laboratory studies (Neitch and others, 1999; Vroblecky and others, 1999; Orchard and others, 2000; Ma and Burken, 2003).

The poor relation between PCE concentrations in trees and underlying ground water at the Front Street site probably occurs because the tree roots are not in contact with the ground water, and PCE sorbed to soils in the unsaturated zone is not in direct proportion to PCE concentrations in the underlying ground water. Because it is unlikely that roots of trees at the Front Street site are in direct contact with the water table, water (and its associated PCE) taken into the transpiration stream by roots is most likely from the capillary fringe or shallow unsaturated zone, and may be at or near equilibrium with PCE concentrations in soils. If PCE at the water table was being directly incorporated into the tree roots, diffusive exchange with PCE in soil, soil moisture, and vapors in the unsaturated zone would likely modify PCE concentrations in the transpiration stream moving up through the roots. Struckhoff (2003) has shown that diffusive exchange between roots and PCE vapor in the unsaturated zone can be as important or more important than PCE concentrations in the ground water. While Vroblecky and others (1999) demonstrated that concentrations of TCE and cis-DCE in trees at the Savannah River site reflected the distribution of TCE and cis-DCE in the underlying shallow ground water, the depth to the contaminated ground water was less than about 5 ft. In contrast, Cox (2002) did not detect TCE in trees growing above a plume of TCE contaminated ground water at McChord Air Force Base (AFB) in Washington. Although TCE concentrations at the McChord AFB site and Savannah River site were of similar magnitude (tens to a few hundreds of micrograms per liter), the depth to ground water at the McChord AFB site (about 30 ft) was more than six times the depth to ground water at the Savannah River site. Cox (2002) postulated that the absence of TCE in trees at the McChord AFB site might be because ground water at the site was below the depth that tree roots growing at the site could reach in addition to cumulative losses within the plants. The poor quantitative relation between PCE in trees and ground water at the Front Street site is consistent with observations by Cox (2002) and indicates that the depth to the contaminated ground water is an important factor controlling VOC concentrations in trees.

Assessment of Subsurface Contamination at the Former Dry Cleaning Facility

The former dry cleaning facility near the intersection of Wall Street and Miller Street is about 500 ft southwest of the Front Street site (fig. 7). Because of its proximity to contaminated public water-supply wells W1 and W2 (fig. 1), the former dry cleaning facility was considered a possible source of the PCE contamination detected in wells W1 and W2 (Singleton, 1987). However, no sampling was done at the former dry clean-

ing facility during the initial investigations conducted during the late 1980's and early 1990's (Singleton, 1987; Jacobs Engineering Group, Inc., 1994). Dry cleaning operations took place in the southeast corner of the basement of a small (about 35 by 50 ft) two-story building, which currently (2003) is a private residence. Interviews of local residents conducted by the USEPA during the RI of the Front Street site determined that waste dry cleaning fluids were dumped on the land surface in a small (about 20 by 40 ft) area along a short (7 ft high) but steep (45 degree) slope behind the former dry cleaning facility. However, the interviews could not establish the types of dry cleaning fluids used, only that the fluids used were apparently flammable; therefore, probably not TCE or PCE (Shelley Brodie, U.S. Environmental Protection Agency, written commun., March 2003). Because of the uncertainty regarding the type of dry cleaning fluids used, the absence of environmental samples from the site, and proximity to the contaminated city wells, the USEPA conducted reconnaissance sampling of the former dry cleaning facility as part of their investigation of the Front Street site. The site was selected for an initial tree-core reconnaissance because access to the area where waste dry cleaning fluid was reportedly dumped is limited by steep slopes and closely spaced homes.

Initial Site Assessment Using Tree Cores

Because of difficulty contacting various property owners at and in the vicinity of the former dry cleaning facility, the preliminary assessment of the site using tree-core sampling was conducted over a 4-month period from July through October 1999. Core samples were collected from a total of 11 trees at the site and vicinity (fig. 7). Core samples were collected immediately down slope of the building where dry cleaning took place (trees DF-1, DF-2, and HS-3), within and near the area where dumping reportedly occurred (trees HS-1, HS-2, and HS-4) and along a short gravel drive (HS-5) near the dump area. Trees were sampled along the side most likely to face the dumping area. The surface of the dumping area was covered with rocks, gravel, and scrub brush and had obviously been disturbed. Core samples also were collected from two trees (T201 and T202) along an intermittent creek south of the dumping area. None of the core samples contained detectable concentrations of PCE or other chlorinated solvents. However, several unknown VOCs suspected to be hydrocarbons with GC retention times between vinyl chloride and cis-DCE were present in core samples from trees HS-1 and HS-5.

Comparison of Tree-Core Sampling to Traditional Soil Sampling at the Former Dry Cleaning Facility

Five additional trees (DF101 through DF105) were cored in January 2002 to verify the results of the preliminary reconnaissance of the site. These trees were located within and slightly west and down slope of the reported dumping area (fig.

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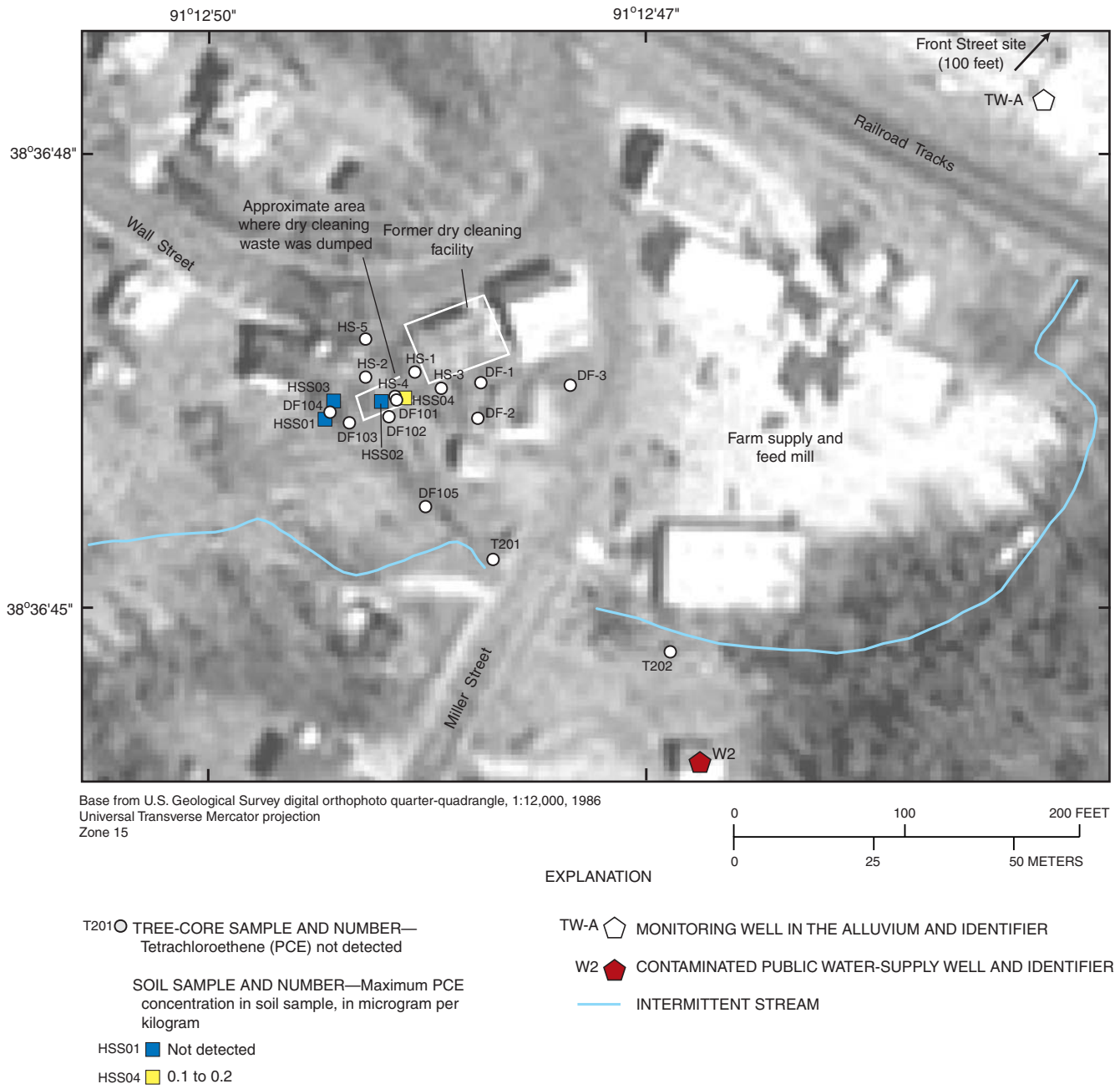


Figure 7. Location of tree-core and soil samples at and in the vicinity of the former dry cleaning facility near downtown New Haven, Missouri.

7). Sample DF105 was a composite of two trees growing along the south property line in the back yard of an adjacent private residence. None of the trees cored in January 2002 contained detectable concentrations of PCE, but trees DF101, DF102, and DF105 contained trace concentrations (0.25 to 1.6 $\mu\text{g-h/kg}$) of toluene (table 2, at the back of this report), and sample DF104 contained a trace concentration (0.73 $\mu\text{g-h/kg}$) of TCE. Because

of the trace concentration of TCE detected in sample DF104, four soil borings (HSS01 to HSS04) were done in February 2002. The soil borings were done using a hand auger and drilled to 3 ft deep. Soil samples were collected at 1 ft intervals and analyzed for VOCs by headspace using the portable GC and by the USGS contract laboratory in Arvada, Colorado, using USEPA method 8260. Soils in borings HSS01, HSS02, and

HSS03 were stained gray and appeared to contain lint or some other powdery material. The presence of stained soils is consistent with information provided by USEPA interviews, which indicated that the waste material from the dry cleaning facility was a gray color. The portable GC detected toluene (0.45 to 21.44 $\mu\text{g-h/kg}$) in samples from boreholes HSS01, HSS02, and HSS03 and a possible trace concentration of PCE (0.16 $\mu\text{g-h/kg}$) in the 1 ft deep sample from borehole HSS04. Laboratory samples did not contain detectable concentrations of PCE or other VOCs.

The results of soil sampling confirmed the tree-core data, indicating the absence of PCE contamination at the former dry cleaning facility. The presence of toluene in several trees and soil samples and gray stained soils suggests that tree-core and soil samples were collected in the area where the dry cleaning waste was disposed. The absence of PCE in tree cores at this site served as a negative control for tree-core sampling at other operable units at the Riverfront Superfund Site.

Practical Considerations in Using Tree-Core Sampling for Site Assessment

Data presented here and ongoing studies at the Riverfront Superfund Site have demonstrated that tree cores can be an effective tool for assessing the presence of subsurface PCE contamination. Data in this report are consistent with other investigations that indicated concentrations of TCE and cis-DCE in trees mimic concentrations of these compounds in underlying shallow (less than 10 ft deep) ground water (Vroblesky and others, 1999; Ma and Burken, 2003). However, Cox (2002) did not detect TCE in trees where the depth to the TCE contaminated ground water was about 30 ft. Research into the mechanisms of VOC incorporation and fate in trees is in its infancy and little is known about the interaction between the many environmental variables that affect tree growth and the distribution of VOCs in the subsurface. Some of these variables include the depth and concentrations of VOCs in the ground water, VOC concentration and distribution in soil and soil vapors, diffusion in the subsurface and diffusive losses from the tree trunk, variability between tree species, variability with tree size, age and root structure, concentration variability around the tree trunk, transpiration rate, and seasonal differences in ground-water concentrations, precipitation, and transpiration rate, among others. The following discussion presents some practical considerations and possible limitations on the use of tree coring for site assessment based on experiences at the Riverfront Superfund Site.

Diffusion Losses and Uptake, Partitioning, and Differences Between Species

Research has shown that VOC diffusion out of tree trunks is a significant loss mechanism to the atmosphere (Ma and Burken, 2002, 2003). More recently, it has been shown that dif-

fusion between tree roots and vapor in the unsaturated zone can lead to significant losses, or uptake of PCE in trees (Struckhoff, 2003). Diffusive loss leads to a profile of decreasing VOC concentrations in tree trunks with increasing height above land surface. Data presented in Vroblesky and others (1999) and from trees growing above a TCE plume at the Aberdeen Proving Ground (Ma and Burken, 2003) indicate that the decrease in VOC concentrations with increasing height is not linear. A similar non-linear decrease in PCE concentrations with increasing height was observed in trees TW02, TW08, and TW28 at the Front Street site (fig. 8). The observed decreases with increasing height in these trees can be closely approximated with an exponential function ($r^2 = 0.96$ to 0.99). However, a linear decrease in PCE concentrations with increasing height was observed in tree TW11 ($r^2 = 0.98$). From the standard diffusion equation, the mass of PCE lost by diffusion from the trunk to the atmosphere should be proportional to the concentration gradient, surface area, and time (approximated by height), and inversely proportional to the path length (approximated by the tree radius). The non-linear decrease in PCE concentrations with increasing height in trees TW02, TW08, and TW28 is probably caused by diffusion loss being driven by a changing concentration gradient. For example, as PCE is lost from the transpiration stream between 1 and 2 ft in height, there is a smaller gradient of PCE (difference between PCE concentration inside and outside the tree) driving diffusion between 2 and 3 ft, and the proportion of PCE lost to PCE remaining, decreases each foot and asymptotically approaches zero.

The diameter of the tree trunk also affects the rate of diffusional loss from the tree. The greater surface area to volume ratio in a smaller diameter section of tree will more quickly deplete the reservoir of PCE in the trunk, decrease the concentration gradient (diffusive driving force), and result in a non-linear concentration loss with increasing height. For example, Struckhoff (2003) showed that a 0.5-in. diameter poplar cutting planted into contaminated soil or water has a 24 percent concentration loss in 5 in. of height, whereas tree TW11 (a 6.5-in. diameter Chinese elm) has the same percent loss in 5 ft of height—about a ten-fold difference. This difference is similar to the calculated volume-to-area ratios of trees (2 divided by the radius) with diameters of 0.5 and 6.5 in. of about 7. The linear loss in PCE concentrations with increasing height in tree TW11 also may be a function of the growth pattern of the tree. Trees TW02, TW08, and TW28 have relatively straight trunks, whereas the trunk of tree TW11 (Chinese elm) forked about every 4 to 5 ft. Compared to the other trees, tree TW11 is unusual in that its incremental volume and surface area decreased as a linear function with height, and interestingly, so did its PCE concentrations.

In addition to diffusion loss of VOCs from the tree trunks, there is some indirect evidence that PCE in soil vapors can diffuse into tree roots at the Riverfront Superfund Site. This mechanism of PCE incorporation into trees at the site was postulated by Schumacher (2001). Concentrations of PCE in soil gas were measured monthly from July 2002 through April 2003 in samples collected along the north side of the Front Street building.

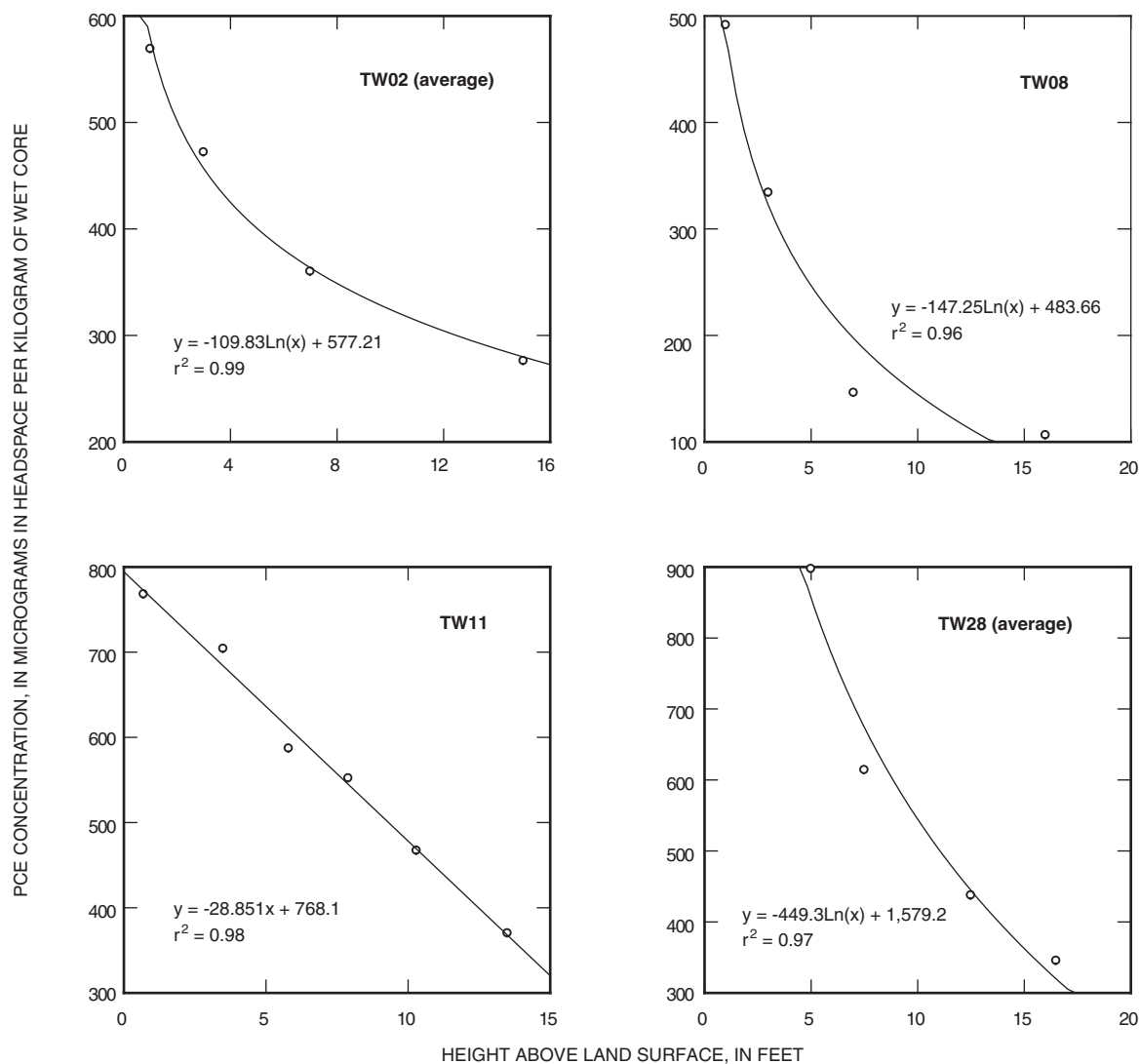


Figure 8. Relation between tetrachloroethene (PCE) concentrations in tree-core samples and height above the land surface.

Soil-gas samplers were installed in clusters at depths of 3.5, 9.0, 12.0, and 14.5 ft deep adjacent to trees TW02, TW06, and TW08. A logarithmic increase (r^2 of 0.92) in PCE concentration in soil gas with increasing depth was observed with the maximum detected PCE concentrations ranging from 1.1 ppmV (parts per million volume) at 3.5 ft deep to 104 ppmV at 14.5 ft deep (fig. 9). The dramatic increase in PCE concentration with increasing depth indicates that the diffusion of PCE into roots from vapors in the unsaturated zone may be significant. The average measured PCE concentration (about 50 ppmV) in soil-gas samplers below 10 ft deep was smaller than the theoretical average concentration of 260 ppmV calculated using PCE concentrations, moisture contents, and organic carbon contents measured in soil samples from the site. During purging, the soil-gas samplers lost vacuum within one to two seconds, indicating porous subsurface conditions. The smaller than expected mea-

sured PCE concentrations in soil gas may be related to vapor loss to the atmosphere.

An experiment was done to determine if PCE vapors in the unsaturated zone could be a source of PCE in trees. Two small (0.5-in. diameter by 16-in. long) poplar cuttings were planted above contaminated soils adjacent to the south side of the Front Street building, and two were placed above contaminated soils at another operable unit (OU2) (fig. 1). The poplar cuttings were planted in potting soil inside bags constructed from an agricultural mesh that excluded roots. The bags were planted above, but not within contaminated soils and watered weekly with tap water. After 2 months, the cuttings and soil inside the mesh bags were sampled. Two of the cuttings that survived contained measurable concentrations of PCE (80.1 $\mu\text{g-h/kg}$ in the cutting from the Front Street site and 242 $\mu\text{g-h/kg}$ in the cutting from OU2). No PCE was detected in soil samples from within the bags. A

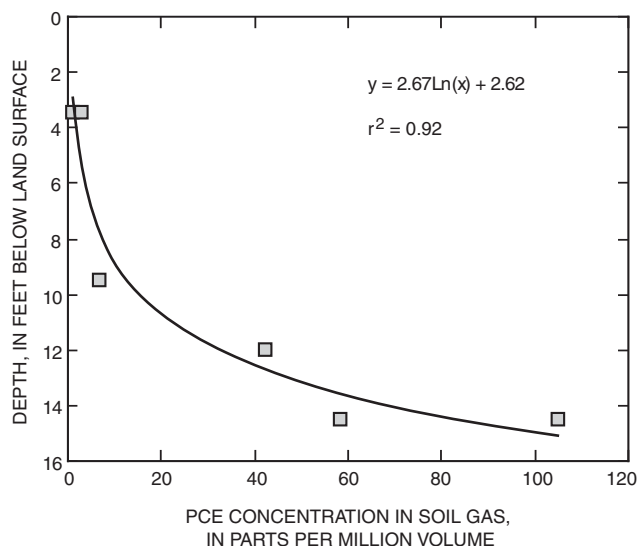


Figure 9. Relation between tetrachloroethene (PCE) concentration in soil gas and depth below the land surface along the north side of the Front Street building.

soil-gas sampler placed within the mesh bag of a poplar cutting on the south side of the Front Street building contained PCE at about 0.2 ppmV (about 0.001 $\mu\text{g}/\text{L}$ air). The detection of PCE in this soil-gas sampler and the poplar cuttings in the mesh bags strongly suggests that PCE in soil vapor accumulates in tree roots at this site.

During the 1999 initial assessment, it was thought that a significant fraction of VOCs in tree-core samples was within the water fraction of the core, and that partitioning from the core into the vial headspace was similar to that from water to air. As a result, VOC concentrations in tree-core samples were originally reported in units of micrograms per liter of core water (Schumacher, 2001). Other researchers such as Vroblesky and others (1999) have normalized VOC concentrations in core samples to core water content. While water content is important, recent studies by Ma and Burken (2002, 2003) and Struckhoff (2003) have shown that the predominant mass of VOCs in tree trunks resides in the wood tissue. Struckhoff (2003) calculated a PCE water-wood (K_{1w}) partitioning coefficient of 0.049 L/g (liter per gram) indicating that PCE is about 20 times more concentrated in the wood phase than the water phase. Core samples from trees at the Riverfront Superfund Site averaged about 50 percent by weight water indicating that more than 95 percent of the PCE in the trees resides in the wood and not the transpiration stream. Field data collected from tree TW28 at the Front Street site substantiate the K_{1w} value derived by Struckhoff (2003). Concentrations of PCE in sap samples collected from tree TW28 at 7.0 and 19 ft above the land surface were 36.8 and 13.6 $\mu\text{g}/\text{L}$, respectively (table 2). These concentrations are comparable to concentrations of 12.9 and 10.1 $\mu\text{g}/\text{L}$ calculated using PCE concentrations determined in core samples at these heights and the K_{1w} (0.049 L/g) value determined by Struckhoff (2003).

Although concentrations of PCE may vary depending on the tree species sampled, data from the Front Street site were not conclusive. In general, there were few locations where multiple species of trees existed in proximity to one another. For example, the average PCE concentrations in core samples collected from tree TW28 on June 30, 2003, at heights of 3, 7, and 16 ft (587, 412, and 268 $\mu\text{g}\text{-h}/\text{kg}$) were about twice as large as the average PCE concentrations in core samples collected from tree TW08 at the same heights (334, 176, and 106 $\mu\text{g}\text{-h}/\text{kg}$). Tree TW28 is an 8-in. diameter Chinese elm and tree TW08 is an 8-in. diameter mulberry that are growing less than 3 ft apart along the north side of the Front Street building. Concentrations of PCE in tree TW28 exhibited considerable directional variability that may be related to diffusion of vapors from beneath the building slab. The average PCE concentration on the north side of tree TW28 (277 $\mu\text{g}\text{-h}/\text{kg}$) was similar to the average PCE concentration on the south side of tree TW8 (253 $\mu\text{g}\text{-h}/\text{kg}$). The PCE concentration of 717 $\mu\text{g}\text{-h}/\text{kg}$ in tree JS77 (an 18-in. diameter buckeye) was substantially larger than the PCE concentration of 90.3 $\mu\text{g}\text{-h}/\text{kg}$ measured in a nearby sweet gum (tree JS80). Vroblesky and others (1999) noted differences in VOC concentrations between tree species at the Savannah River site with bald cypress, tupelo, and loblolly pine containing larger TCE concentrations than nearby oak and sweet gum. The limited data from the Front Street site suggest that, although there may be a difference in the uptake of PCE between different tree species (for example, elm and buckeye may uptake PCE to a greater extent than mulberry or sweet gum), this difference may be overshadowed by directional variability around the tree trunk.

Directional Variability in Tree Trunks

Concentrations of PCE exhibited directional variability around tree trunks, which makes the location of the core sample an important factor to consider when using tree coring as a site assessment tool. For example, PCE concentrations in core samples collected from tree TW02 at 1.5 and 7 ft above the land surface on July 9, 2003, varied by a factor of about 3 to 5 around the circumference of the tree (table 3). This variability is the result of spatial differences in PCE concentrations in soils around the tree and natural "twisting" of the tree trunk with growth. The smallest PCE concentrations (about 20 to 35 percent of the maximum concentration detected) at each height were on the southwest side of the tree (fig. 10). This part of the tree was growing above a concrete storm drain cover buried about 1.5 ft below the soil surface. The small PCE concentrations on this side of the tree were expected because the soils above this slab had no detectable PCE concentrations and presumably roots growing above the slab are in contact with uncontaminated soils and infiltration. The fact that any PCE was detected on this side of the tree may indicate diffusion from areas of larger PCE concentrations in the trunk or diffusion of PCE vapors through the unsaturated zone into the area above the concrete slab. From the exterior of the tree, it is apparent that the

Table 3. Variation in tetrachloroethene (PCE) concentrations in the trunk of tree TW02 with direction and height above the land surface

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene]

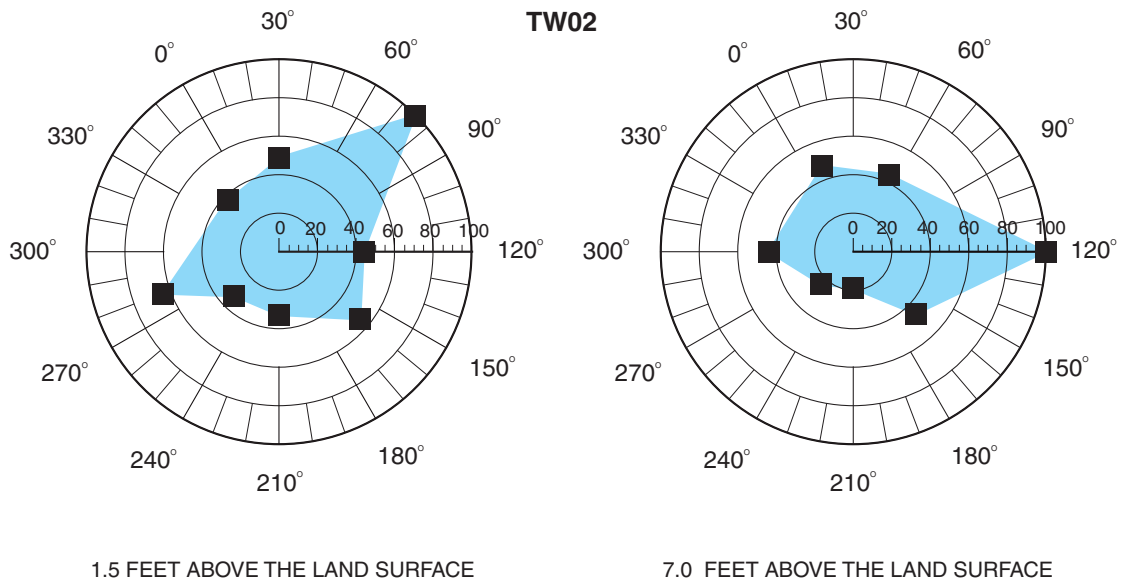
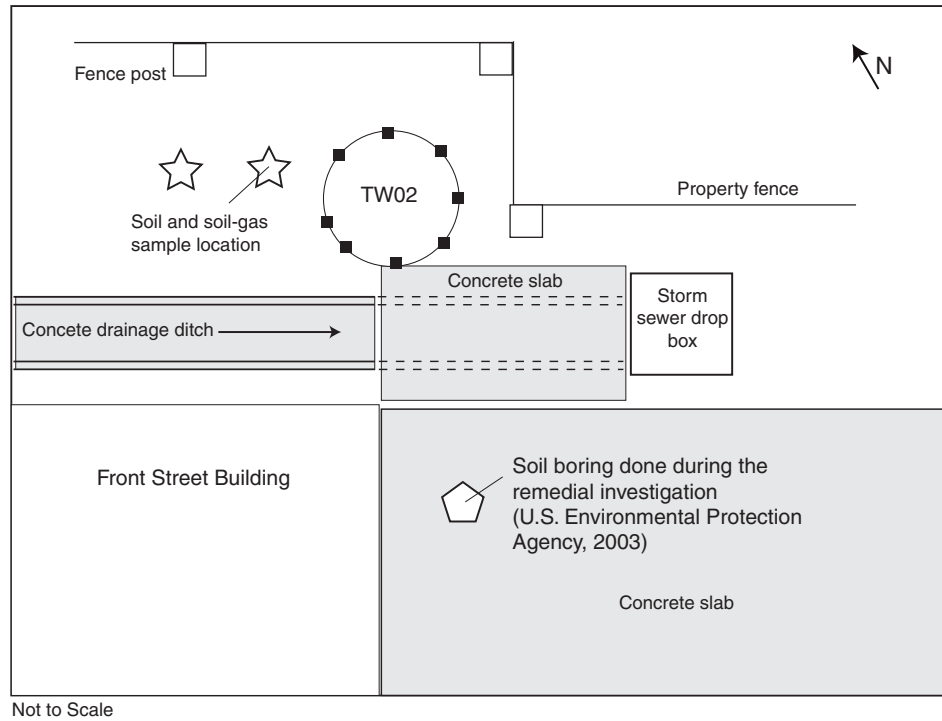
Tree identifier	Height above the land surface (feet)	Date	PCE	Azimuth (degrees from true north)
OU1-TW02	1	06/30/03	1,010	75
OU1-TW02	1	06/30/03	339	255
OU1-TW02	1	06/30/03	360	5
OU1-TW02	1.5	07/09/03	368	30
OU1-TW02	1.5	07/09/03	755	75
OU1-TW02	1.5	07/09/03	329	120
OU1-TW02	1.5	07/09/03	415	165
OU1-TW02	1.5	07/09/03	252	210
OU1-TW02	1.5	07/09/03	480	280
OU1-TW02	1.5	07/09/03	286	345
OU1-TW02	3	06/30/03	685	75
OU1-TW02	3	06/30/03	228	255
OU1-TW02	3	06/30/03	506	5
OU1-TW02	6	07/09/03	404	55
OU1-TW02	6	07/09/03	921	120
OU1-TW02	6	07/09/03	423	165
OU1-TW02	6	07/09/03	179	210
OU1-TW02	6	07/09/03	219	255
OU1-TW02	6	07/09/03	404	300
OU1-TW02	6	07/09/03	437	10
OU1-TW02	7	06/30/03	386	75
OU1-TW02	7	06/30/03	151	255
OU1-TW02	7	06/30/03	543	5
OU1-TW02	15	06/30/03	303	75
OU1-TW02	15	06/30/03	249	255

trunk of this eastern red cedar twists in a clockwise direction. The PCE concentrations reflect this twisting of the trunk as the maximum concentration shifted from east at 1.5 ft in height to the southeast at 7 ft in height (fig. 10). The largest concentration detected at the 7 ft height (921 $\mu\text{g-h/kg}$) actually was about 20 percent larger than the maximum concentration detected at the 1.5 ft height (755 $\mu\text{g-h/kg}$). Diffusion from the trunk should cause concentrations to decrease with increasing height above the land surface, and the larger concentration in the 7 ft sample suggests that the density of sampling points around the tree was not sufficient to completely resolve the directional variability around the trunk.

Directional variability also was observed in tree TW28. This tree is growing adjacent to the Front Street building, and it was impossible to core all sides of the tree at various heights above land surface. Core samples collected from the south side of the tree had almost four times the PCE concentrations of those collected from the north side of the tree (fig. 11). The large PCE concentrations on the south side of this tree compared to the north are unexpected because PCE concentrations in soil and ground-water samples in proximity to this tree are similar. Because this tree is growing adjacent to the building, it

is possible that roots on the south side must reach deeper to obtain sufficient soil moisture, or that the building slab acts like a cap trapping PCE vapors in localized areas. Soil samples collected adjacent to tree TW28 indicates a dramatic increase in PCE concentrations from less than 500 $\mu\text{g/kg}$ at less than 10 ft deep to more than 7,000 $\mu\text{g/kg}$ at depths below 14 ft (U.S. Environmental Protection Agency, 2003). Large concentrations of PCE vapors in the unsaturated zone were observed during the excavation of a contaminated water line beneath Front Street on the south side of the building, and it is possible that these vapors may be migrating through the gravel backfill beneath the building slab in the vicinity of tree TW28.

The directional variability in very small diameter trees may not be evident because of their small root footprint, the large ratio of core sample to trunk volume, and the fact that a single core may easily penetrate nearly the entire diameter of the tree. Ma and Burken (2003) showed that TCE concentrations decreased towards the exterior of a hybrid poplar tree growing at the Aberdeen Proving Ground site. While providing additional evidence for diffusion, the decrease toward the exterior of the tree indicates that core samples collected from larger trees may underestimate VOC concentrations in the trunk



PERCENTAGE OF THE MAXIMUM PCE CONCENTRATION DETECTED AT EACH HEIGHT. DIRECTION IN DEGREES FROM NORTH

Figure 10. Directional variability in tetrachloroethene (PCE) concentrations in core samples from an eastern red cedar tree (TW02).

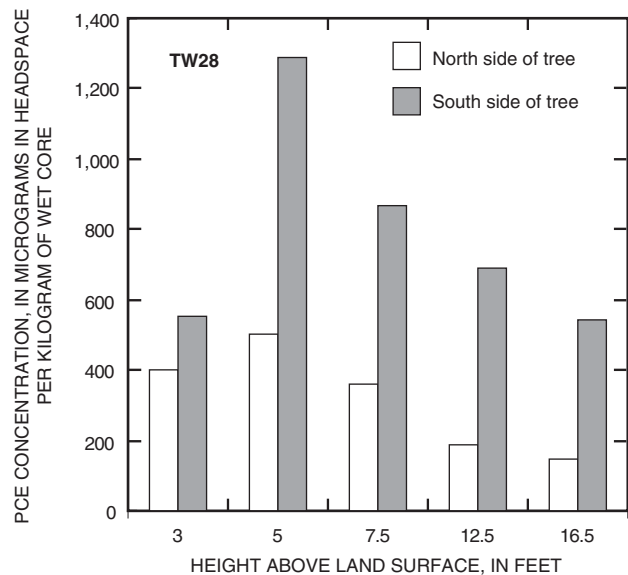


Figure 11. Directional variability in tetrachloroethene (PCE) concentrations in core samples collected from tree TW28 on June 30, 2003.

because they are sampling a disproportionately larger volume of wood that contains smaller VOC concentrations.

Sensitivity of Tree-Core Sampling to Detect Subsurface Contamination

An important consideration in using tree-core analysis to assess subsurface VOC contamination is the overall sensitivity of the technique to detect contamination. A wide variety of factors undoubtedly affect the ratio of VOCs such as PCE in a tree to concentrations in the underlying soil, soil vapors, and ground water. Laboratory hydroponic studies (Ma and Burken, 2002, 2003) have shown that TCE concentrations in the transpiration stream of hybrid poplar trees are about 0.2 to 0.75 times the concentration observed in simulated ground water. However, these studies were performed at simulated ground-water TCE concentrations of 50,000 µg/L. Of interest for the Riverfront Superfund Site was an estimate of the potential lower threshold of ground-water concentrations that could possibly be detected in trees; that is, the sensitivity of the method to detect subsurface contamination.

A field hydroponic experiment was conducted to provide an estimate of the maximum sensitivity of tree-core samples to detect PCE contamination in ground water in contact with the tree roots. In the experiment, six hybrid poplar cuttings (approximately 0.5-in. diameter by 12-in. long) were planted directly into each of two PCE contaminated streams, the 500 tributary and the 210 tributary (fig. 1). The cuttings were planted at low-flow conditions on July 30, 2003, and removed 8 days later. The 500 tributary is southwest of operable unit OU2, and is affected by PCE contamination from that facility (U.S. Environmental

Protection Agency, 2003). The 210 tributary is affected by an unknown PCE source in operable unit OU4. Stream discharge and PCE concentrations were measured at days 1 and 8. On day 8, the cuttings were removed and samples from them were analyzed by headspace GC as previously described. During the experiment, the average PCE concentration in water samples collected from the 500 tributary was 83 µg/L and its discharge was estimated at 18 gal/min (gallons per minute). The 210 tributary water samples contained an average PCE concentration of 22 µg/L and had an estimated discharge of about 0.03 gal/min.

Samples from poplar cuttings placed in the 500 tributary contained an average PCE concentration of 135 µg-h/kg in the stem sampled just above the water, yielding a calculated transpiration stream concentration of 14 µg/L. Samples from cuttings placed in the 210 tributary contained an average PCE concentration of 31 µg-h/kg in the stem sampled just above the water surface, and a calculated transpiration stream concentration of 4.6 µg/L. The above concentrations were calculated using the measured headspace concentrations of PCE, wet and dry mass of core samples, and water-wood (K_{lw}) and air-plant or air-core (K_{aw}) partitioning coefficients for PCE in hybrid poplar trees reported by Struckhoff (2003). The relations between PCE concentrations in the vapor (headspace), wood (dry core), and liquid phase (water in the core) are:

$$K_{lw} = 0.049 = \frac{C_{dw}}{C_l}, \quad K_{aw} = 0.0081 = \frac{C_t}{C_a}$$

where:

C_{dw} = the PCE concentration in the dry wood (dried core sample), in milligrams per gram;

C_l = the PCE concentration in the aqueous phase in the core sample (such as transpiration stream), in milligrams per liter;

C_t = the PCE concentration in the plant (wet core sample), in micrograms per gram; and

C_a = the PCE concentration in the air or headspace, in micrograms per liter.

These results lead to a PCE transpiration stream concentration factor (TSCF) of about 0.2. The calculated TSCF is the ratio of the PCE concentration in the transpiration stream to the PCE concentration in the water entering the roots (average PCE concentration in the tributaries). Because these trees were sampled directly above the water in which they were growing, there was very little chance for PCE to diffuse from the tree stem into the atmosphere. These results represent the anticipated upper limit of PCE transport in a poplar tree compared to the ground water in contact with the roots under field conditions. The overall findings of this report and related research (Struckhoff, 2003) introduce a new mechanism, vapor phase exchange, in VOC uptake and translocation. The degree of vapor phase exchange in the subsurface can then alter the observed TSCF at different sites.

A comparison of the ratios of PCE concentration in the poplar cuttings and streams in the field hydroponic tests (about 1.4 to 1.6) indicates that at a headspace method detection limit (MDL) of about 0.8 $\mu\text{g-h/kg}$, a PCE concentration of 0.5 $\mu\text{g/L}$ theoretically could be detected in ground water using tree-core analysis. This is a “best-case scenario”, however, and this sensitivity cannot be achieved in the natural settings because the field hydroponic experiment did not take into account losses within the roots and trunk.

A better indication of the practical sensitivity of the tree-core method is the ratio of PCE concentrations in core samples collected from trees growing adjacent to the 500 and 210 tributaries to those in the water. Core samples collected from willow trees adjacent to the 500 tributary at the conclusion of the field hydroponic experiment in 2003 contained an average PCE concentration of 10 $\mu\text{g-h/kg}$; using the average PCE concentration in tributary 500 (83 $\mu\text{g/L}$), a tree core/water ratio of about 0.1 is obtained. Core samples collected during April 2001 from several hackberry, elm, and oak trees growing along the 210 tributary contained estimated PCE concentrations of 0.23 to 0.52 $\mu\text{g-h/kg}$ (average of 0.4 $\mu\text{g-h/kg}$) (U.S. Environmental Protection Agency, 2003). The average PCE concentration along the reach of the 210 tributary during April 2001 when the tree-core samples were collected was 12 $\mu\text{g/L}$ (U.S. Environmental Protection Agency, 2003), giving a tree core/water ratio of about 0.03. A comparison of these ratios to the headspace MDL of about 0.8 $\mu\text{g-h/kg}$ indicates that detectable PCE concentrations should be present in trees in contact with ground water containing PCE concentrations in the range of 8 to about 30 $\mu\text{g/L}$. Even under the best conditions, it seems unlikely that analysis of tree cores at this site could reliably detect ground-water contamination at the current MCL of 5 $\mu\text{g/L}$ or smaller.

The sensitivity of tree cores to detected PCE contamination in soils is difficult to estimate because PCE concentrations in soils at OU1 typically are large (tens of thousands of micrograms per kilogram or more) and because of the potential for a mixture of contaminated soil, soil vapor, and ground water at most locations at OU1. Detectable concentrations of PCE have been found in core samples from trees at the Front Street site that are growing in soil contaminated with as little as a few tens to hundreds of micrograms per kilogram. In addition, PCE was detected in hybrid poplar cuttings planted in soils at operable unit OU2 that contained PCE concentrations less than 1,000 $\mu\text{g/kg}$. The data indicate that PCE should be present in core samples from trees growing in soils containing PCE concentrations of several hundred micrograms per kilogram or less.

Summary and Conclusions

Tree-core sampling has been a reliable and inexpensive tool to quickly assess the presence of shallow (less than about 30 feet deep) tetrachloroethene (PCE) and trichloroethene (TCE) contamination in soils and ground water at the Riverfront Superfund Site. Tree-core sampling was used during the initial

assessment of two sites, the Front Street site (operable unit OU1), and the former dry cleaning facility, that are part of the overall Riverfront Superfund Site. Results of tree-core sampling were later compared to, and confirmed by, traditional soil and ground-water sampling at these two sites. Tree-core sampling detected the presence of subsurface PCE contamination at the Front Street site and beneath private property downgradient from the site. Tree-core sampling did not indicate PCE contamination at the former dry cleaning facility, a finding that was confirmed by later soil sampling.

The Front Street site is on the Missouri River alluvium and has large PCE concentrations in soil [as large as 6,200,000 $\mu\text{g/kg}$ (micrograms per kilogram)] and ground water [as large as 11,000 $\mu\text{g/L}$ (micrograms per liter)]. The lateral extent of PCE contamination in trees at this site was in close agreement with the extent of subsurface PCE contamination determined using traditional soil and ground-water sampling. Trees growing in soils containing PCE concentrations of 60 to 5,700 $\mu\text{g/kg}$ or larger, or overlying ground water containing PCE concentrations in the tens to as large as 11,000 $\mu\text{g/L}$, generally contained detectable concentrations of PCE. Depth to contaminated ground water is about 20 to 25 feet below the land surface.

A variety of conventions have been used to express volatile organic compound (VOC) concentrations in tree-core samples. The convention chosen for this report was to express concentrations as mass in the vial headspace per mass of wet core. This convention requires that only the volume of the core placed in the vials be known. The core volume was estimated from the mass of core placed in the vial assuming that the core density was 1.0 g/cm^3 (gram per cubic centimeter). This assumption introduces a small (less than 5 percent) error in the calculated headspace concentrations at wood densities ranging from 0.6 to 1.0 g/cm^3 that are typical for trees growing at the site. Another popular convention is to express VOC concentrations as concentration in the headspace per mass of water in the core. This convention may introduce error because the partitioning coefficients generally are not known for each compound of interest and each tree species sampled.

Significant quantitative relations [probability (p) values of less than 0.05 and correlation coefficient (r^2) values of 0.88 to 0.90] were found between PCE concentrations in trees and subsurface soils between 4 and 16 feet deep. The best fit (r^2 of 0.90) was obtained between PCE in trees and soils at 12 feet below the surface according to the relation $\log(\text{PCE in tree, in micrograms in headspace per kilogram of wet core}) = 0.598 * \log(\text{PCE in soil, in micrograms per kilogram})$. The relation between PCE concentrations in trees and underlying PCE contaminated ground water was less apparent (r^2 value of 0.17). The quantitative relation between PCE concentrations in trees and soils at this site is thought to represent the distribution of PCE in soils and soil vapors caused by direct disposal of PCE to the surface in some parts of the site and by the sorption of PCE to soils in downgradient areas caused by seasonal rises in underlying contaminated ground water. The seasonal rises are driven by changes in stage of the Missouri River.

While it was beyond the scope of this field-oriented study to investigate the various mechanisms that affect the incorporation and loss of PCE in trees, several observations consistent with published studies were noted. An exponential decrease in PCE concentrations in tree-core samples with increasing height above the land surface was observed in most trees. This loss was consistent with diffusion of VOCs from tree trunks postulated by other researchers at the Savannah River site in the late 1990's and recently confirmed in laboratory studies at the University of Missouri-Rolla. The rate of loss also appeared to be a function of the size and growth characteristics of the tree. Loss of PCE in small (0.5-inch) diameter trees was observed to occur at a rate more than ten times faster than in trees 6.5 inches in diameter. In addition to loss of PCE by diffusion, there is indirect evidence from the site that PCE vapors in the unsaturated zone can diffuse into tree roots. PCE was observed in poplar tree cuttings planted in uncontaminated potting soil above PCE contaminated soils at the site. Soil-gas measurements confirmed the presence of PCE vapor adjacent to the roots of the poplar cuttings and PCE concentrations in soil gas were observed to increase logarithmically with increased depth at the site.

Concentrations of PCE also exhibited directional variability around the tree trunks. Three- to five-fold concentration differences were observed around the trunks of several trees growing along the north side of the Front Street building. In one tree, the directional differences were attributable to spatial differences in PCE concentrations in soils around the tree. In the other instance, the differences may be caused by diffusion of PCE vapors in the unsaturated zone into the tree roots. Directional differences in PCE concentrations around the tree trunks also were related to natural "twisting" of tree trunks. PCE concentrations may be dependent upon the tree species, with Chinese elm and buckeye tending to have larger concentrations than adjacent or nearby mulberry or sweet gum. The concentration differences between species at this site may be overshadowed by directional variability around the tree trunks.

The sensitivity of tree-core sampling to detect subsurface contamination was estimated using measured PCE concentrations in trees growing along contaminated tributaries at the Riverfront Superfund Site and from field hydroponic experiments. Data collected from trees growing along PCE-contaminated streams and hybrid poplar cuttings planted in these streams indicate that tree-core sampling can be used to detect PCE concentrations as small as about 8 to 30 $\mu\text{g/L}$ in shallow ground water at this site. This range assumes that the tree roots are in direct contact with the contaminated ground water, and that the depth to ground water is less than a few feet deep. The sensitivity of tree cores to detected PCE contamination in soils is difficult to estimate because PCE concentrations in soils at the Front Street site typically are large (tens of thousands of micrograms per kilogram or more), and because a mixture of contaminated soil, soil vapor, and ground water is present at most locations at the Front Street site. The data indicate that PCE should be present in core samples from trees growing in soils containing

PCE concentrations of several hundred micrograms per kilogram or less.

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TABLE

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft., feet; DS, downstream]

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
Trees sampled at the Front Street site								
OU1-JS113	3	09/05/01	0.88	<0.8	<10	<0.8	<0.8	20 in. Apple
OU1-JS62	3	04/18/01	1.12	<8	<10	<8	<8	10 in. Ornamental cherry
OU1-JS62	3	04/18/01	.58 J	<8	<10	<8	<8	10 in. Ornamental cherry
OU1-JS63	3	04/18/01	.59 J	<8	<10	<8	<8	20 in. Boxelder
OU1-JS63	3	04/18/01	.25 J	<8	<10	<8	<8	20 in. Boxelder
OU1-JS64	3	04/18/01	32.8	.18	<10	<8	<8	13 in. Pecan
OU1-JS64	3	04/18/01	26.5	.10	<10	<8	<8	13 in. Pecan
OU1-JS64	0	09/05/01	<8	<8	<10	<8	.24 J	11 in. Apple, NW side of tree
OU1-JS64	0	09/05/01	<8	<8	<10	<8	.17 J	11 in. Apple, NW side of tree
OU1-JS64	0	09/05/01	<8	<8	<10	<8	.18 J	Apple core, SO side of tree
OU1-JS64	3	09/05/01	117.25 J	<8	.04 J	<8	<8	13 in. Pecan
OU1-JS65	3	04/18/01	4.43	.56	2.00 J	<8	<8	10 in. Mulberry, 3 trunks
OU1-JS66	3	04/18/01	.72 J	.07	.19 J	<8	<8	11 in. Apple
OU1-JS66	3	04/18/01	.85	.12	.24 J	<8	<8	11 in. Apple
OU1-JS66	0	09/05/01	<8	<8	<10	<8	<8	Apple fruit sample
OU1-JS66	0	09/05/01	<8	<8	<10	<8	<8	Apple fruit sample
OU1-JS66	0	09/05/01	.1 J	<8	<10	<8	<8	Apple fruit sample
OU1-JS66	3	09/05/01	.96	<8	<10	<8	<8	10 in. Apple
OU1-JS67	3	04/18/01	14.5	.03	.1 J	<8	<8	13 in. Pecan
OU1-JS67	3	04/18/01	7.47	.03	.1 J	<8	<8	13 in. Pecan
OU1-JS68	3	04/18/01	<8	<8	<10	<8	<8	17 in. Silver maple
OU1-JS70	3	04/19/01	<8	<8	<10	<8	<8	8 in. Ash
OU1-JS77	3	04/21/01	717	6.48	<10	<8	<8	18 in. Buckeye
OU1-JS78	3	04/21/01	16.4	.09	<10	<8	<8	10 in. Mulberry
OU1-JS79	3	04/21/01	6.54	<8	<10	<8	<8	9 in. Walnut
OU1-JS80	3	04/21/01	90.3	.59	<10	<8	<8	34 in. Sweet gum
OU1-TA02	3	04/19/01	.41 J	<8	<10	<8	<8	10 in. Birch
OU1-TCR01	3	11/27/00	<8	<8	<10	<8	<8	8 in. Sycamore, next to well TW-G
OU1-TCR02	3	11/27/00	<8	<8	<10	<8	<8	14 in. Boxelder, west TW-G (xylene and ethyl benzene detected)
OU1-TCR03	3	11/27/00	<8	<8	<10	<8	<8	10 in. Boxelder, 2 trunks

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003—Continued

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft, feet; DS, downstream]

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
Trees sampled at the Front Street site—Continued								
OUI-TCR04	3	11/27/00	0.98	<0.8	1.24	<0.8	<0.8	8 in. Sycamore
OUI-TCR05	3	11/27/00	<.8	<.8	<10	<.8	<.8	14 in. Sycamore
OUI-TCR06	3	11/27/00	<.8	<.8	<10	<.8	<.8	8 in. Boxelder
OUI-TCR07	3	11/27/00	<.8	<.8	<10	<.8	<.8	13 in. Rock elm
OUI-TCR08	3	11/27/00	<.8	<.8	<10	<.8	<.8	6 in. Sycamore, 2 trunks
OUI-TW01	3	04/11/01	<.8	<.8	<10	<.8	<.8	11 in. Twin mulberry
OUI-TW01	3	04/11/01	.33 J	.72 J	6.0 J	<.8	<.8	11 in. Twin mulberry
OUI-TW02	3	06/29/00	197	<.8	<10	<.8	25.1	10 in. Eastern red cedar
OUI-TW02	3	02/06/01	35.4	.15 J	.2 J	.05 J	3.39	10 in. Eastern red cedar
OUI-TW02	3	04/11/01	254	.72 J	5.8 J	<.8	9.19	10 in. Eastern red cedar
OUI-TW02	3	04/11/01	302	3.41	14.7	<.8	57.6	10 in. Eastern red cedar
OUI-TW02	3	04/11/01	141	<.8	1.3 J	<.8	28.9	10 in. Eastern red cedar
OUI-TW02	3	06/27/01	130	.47 J	.2 J	2.19	7.58	10 in. Eastern red cedar
OUI-TW02	3	09/05/01	272	8.23	<10	<.8	17.8	10 in. Eastern red cedar
OUI-TW02	3	11/27/01	270	22.2	1.4 J	<.8	50.1	10 in. Eastern red cedar
OUI-TW02	3	02/12/02	148	<.8	5.5 J	<.8	7.51	10 in. Eastern red cedar
OUI-TW02	3	07/01/02	1,020	<.8	<10	<.8	<.8	10 in. Eastern red cedar
OUI-TW02	3	07/01/02	831	<.8	<10	<.8	<.8	10 in. Eastern red cedar
OUI-TW02	3	07/01/02	601	<.8	<10	<.8	<.8	10 in. Eastern red cedar
OUI-TW02	3	06/30/03	316	<.8	<10	<.8	64.8	10 in. Eastern red cedar
OUI-TW03	3	02/06/01	14.5	.27	.2 J	.22 J	<.8	6 in. Chinese elm
OUI-TW03	3	04/11/01	15.6	.30	<10	<.8	<.8	6 in. Chinese elm
OUI-TW03	3	04/11/01	1.79	.26	<10	<.8	<.8	6 in. Chinese elm
OUI-TW03	3	04/11/01	1.84	<.8	1.2 J	<.8	<.8	6 in. Chinese elm
OUI-TW03	3	02/12/02	11.6	.89	6.5 J	<.8	<.8	6 in. Chinese elm
OUI-TW04	3	04/11/01	32.6	<.8	2.35	<.8	<.8	3 in. Mulberry, 2 trunks
OUI-TW04	3	04/11/01	30.3	<.8	10.0	<.8	<.8	3 in. Mulberry, 2 trunks
OUI-TW04	3	04/11/01	1.51	<.8	3.0 J	<.8	<.8	3 in. Mulberry, 2 trunks
OUI-TW06	3	06/29/00	105	1.89	<10	<.8	<.8	3 in. Mulberry
OUI-TW06	3	02/06/01	27.2	.15	5.6 J	.12 J	<.8	3 in. Mulberry

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003—Continued

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft., feet; DS, downstream]

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
Trees sampled at the Front Street site—Continued								
OUI-TW06	3	06/27/01	82.1	10.2	0.9 J	0.04 J	<0.8	3 in. Mulberry
OUI-TW06	3	09/05/01	255	3.23	<10	<8	<8	3 in. Mulberry
OUI-TW06	3	11/27/01	166	41.5	<10	<8	<8	3 in. Mulberry
OUI-TW06	3	02/12/02	240	3.78	<10	<8	<8	3 in. Mulberry
OUI-TW06	3	06/28/02	1,411	<8	<10	<8	<8	3 in. Mulberry
OUI-TW06	3	06/28/02	696	<8	<10	<8	<8	3 in. Mulberry
OUI-TW06	3	06/28/02	490	<8	<10	<8	<8	10 in. Cottonwood
OUI-TW07	3	04/11/01	10.9	<8	<10	<8	<8	10 in. Cottonwood
OUI-TW07	3	04/11/01	6.70	<8	1.3 J	<8	<8	10 in. Cottonwood
OUI-TW07	3	04/11/01	.5 J	<8	5.7 J	<8	<8	10 in. Cottonwood
OUI-TW07	3	11/27/01	33.0	<8	235	<8	<8	10 in. Cottonwood
OUI-TW08	3	06/29/00	151	2.07	<10	<8	<8	8 in. Mulberry
OUI-TW08	3	11/27/01	293	30.8	<10	<8	<8	8 in. Mulberry
OUI-TW08	3	02/12/02	158	2.96	<10	<8	<8	8 in. Mulberry
OUI-TW08	3	02/12/02	113	2.28	<10	<8	<8	8 in. Mulberry
OUI-TW08	3	07/29/02	522	<8	<10	<8	<8	8 in. Mulberry
OUI-TW08	1	06/30/03	736	.77	<10	<8	<8	8 in. Mulberry, NE side
OUI-TW08	1	06/30/03	194	.20	<10	<8	<8	8 in. Mulberry, NW side
OUI-TW08	1	06/30/03	544	.57	<10	<8	<8	8 in. Mulberry, SO side
OUI-TW08	3	06/30/03	614	.64	<10	<8	<8	8 in. Mulberry, NE side
OUI-TW08	3	06/30/03	215	.22	<10	<8	<8	8 in. Mulberry, NW side
OUI-TW08	3	06/30/03	173	.18	<10	<8	<8	8 in. Mulberry, SO side
OUI-TW08	7	06/30/03	224	.23	<10	<8	<8	8 in. Mulberry, NW side
OUI-TW08	7	06/30/03	68.2	.07	<10	<8	<8	8 in. Mulberry, SO side
OUI-TW08	16	06/30/03	98.3	.10	<10	<8	<8	8 in. Mulberry, NO side
OUI-TW08	16	06/30/03	114	.12	<10	<8	<8	8 in. Mulberry, SO side
OUI-TW11	3	06/29/00	1,900	131	9.3 J	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	06/29/00	3,850	249	17.3	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	06/29/00	1,910	131	9.4 J	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	11/27/00	1,914	144	239	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	04/18/01	1,090	62.3	59.7	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	04/18/01	1,010	89.3	101	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	06/27/01	1,930	171	212	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	09/05/01	457	13.82	<10	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	1.5	02/12/02	521	99.8	.9 J	<8	<8	6 in. Chinese elm, SO side

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003—Continued

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft, feet; DS, downstream]

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
Trees sampled at the Front Street site—Continued								
OUI-TW11	3.5	06/28/02	2,460	<0.8	<10	<0.8	<0.8	6 in. Chinese elm, SO side
OUI-TW11	6.5	06/28/02	1,920	<8	<10	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	3	06/28/02	3,310	<8	<10	<8	<8	6 in. Chinese elm, SO side
OUI-TW11	.7	07/09/03	768	--	--	--	--	6 in. Chinese elm, SO side
OUI-TW11	3.5	07/09/03	704	--	--	--	--	6 in. Chinese elm, SO side
OUI-TW11	5.8	07/09/03	587	--	--	--	--	6 in. Chinese elm, SO side
OUI-TW11	7.9	07/09/03	552	--	--	--	--	6 in. Chinese elm, SO side
OUI-TW11	10.3	07/09/03	467	--	--	--	--	6 in. Chinese elm, SO side
OUI-TW11	13.5	07/09/03	370	--	--	--	--	6 in. Chinese elm, SO side
OUI-TW12	3	06/29/00	29.6	<8	<10	<8	<8	2 in. Chinese elm
OUI-TW13	3	04/11/01	<8	<8	1.05	<8	<8	6 in. Mulberry, 4 trunks
OUI-TW13	3	04/11/01	<8	<8	<10	<8	<8	6 in. Mulberry, 4 trunks
OUI-TW13	3	07/29/02	<8	<8	<10	<8	<8	6 in. Mulberry, 4 trunks
OUI-TW14	3	04/11/01	<8	<8	<10	<8	<8	6 in. Mulberry
OUI-TW14	3	04/11/01	2.23	<8	23.0	<8	<8	6 in. Mulberry
OUI-TW14	3	07/29/02	<8	<8	<10	<8	<8	6 in. Mulberry
OUI-TW15	3	04/11/01	<8	<8	<10	<8	<8	4 in. Mulberry
OUI-TW15	3	04/11/01	<8	<8	13.5	<8	<8	4 in. Mulberry
OUI-TW15	3	07/29/02	<8	<8	<10	<8	<8	4 in. Mulberry
OUI-TW16	3	04/11/01	1.62	<8	5.12	<8	<8	4 in. Catalpa
OUI-TW16	3	04/11/01	1.61	<8	1.96	<8	<8	4 in. Catalpa
OUI-TW16	3	07/29/02	<8	<8	<10	<8	<8	4 in. Catalpa
OUI-TW17	3	04/11/01	1.51	<8	<10	<8	<8	3 in. Chinese elm
OUI-TW17	3	04/11/01	2.76	<8	<10	<8	<8	3 in. Chinese elm
OUI-TW18	3	07/29/02	134	<8	<10	<8	<8	4 in. Chinese elm, 2 trunks
OUI-TW19	3	07/29/02	495	<8	<10	<8	<8	3 in. Chinese elm
OUI-TW20	3	07/29/02	<8	<8	<10	<8	<8	4 in. Ash
OUI-TW21	3	07/29/02	<8	<8	<10	<8	<8	4 in. Chinese elm
OUI-TW22	3	07/29/02	29.3	<8	<10	<8	<8	3 in. Chinese elm, 5 trunks
OUI-TW23	3	07/29/02	<8	<8	<10	<8	<8	4 in. Silver maple
OUI-TW24	3	07/29/02	<8	<8	<10	<8	<8	4 in. Silver maple
OUI-TW25	3	07/29/02	<8	<8	<10	<8	<8	5 in. Chinese elm
OUI-TW26	3	07/29/02	<8	<8	<10	<8	<8	3 in. Walnut
OUI-TW27	3	07/29/02	<8	<8	<10	<8	<8	4 in. Mulberry, 2 trunks
OUI-TW28	3	07/29/02	1,090	<8	<10	<8	<8	8 in. Chinese elm

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003—Continued

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft, feet; DS, downstream]

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
Trees sampled at the Front Street site—Continued								
OUI-TW28	1	06/30/03	307	0.32	<10	<0.8	<0.8	8 in. Chinese elm
OUI-TW28	3	06/30/03	267	.28	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	3	06/30/03	907	.94	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	7	06/30/03	506	20.5	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	7	06/30/03	318	.33	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	12	06/30/03	405	19.4	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	12	06/30/03	318	.33	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	16	06/30/03	319	.21	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	16	06/30/03	216	.22	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	19	06/30/03	307	.32	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28	19	06/30/03	306	.32	<10	<.8	<.8	8 in. Chinese elm
OUI-TW28 sap	7	06/30/03	36.8	<.8	--	--	--	Sap from 8 in. Chinese elm
OUI-TW28 sap	19	06/30/03	13.6	<.8	--	--	--	Sap from 8 in. Chinese elm
OUI-TW28	1	07/30/03	312	--	--	--	--	8 in. Chinese elm
OUI-TW28	3	07/30/03	401	--	--	--	--	8 in. Chinese elm
OUI-TW28	3	07/30/03	551	--	--	--	--	8 in. Chinese elm
OUI-TW28	5	07/30/03	504	--	--	--	--	8 in. Chinese elm
OUI-TW28	5	07/30/03	1,290	--	--	--	--	8 in. Chinese elm
OUI-TW28	7.5	07/30/03	359	--	--	--	--	8 in. Chinese elm
OUI-TW28	7.5	07/30/03	869	--	--	--	--	8 in. Chinese elm
OUI-TW28	12.5	07/30/03	186	--	--	--	--	8 in. Chinese elm
OUI-TW28	12.5	07/30/03	689	--	--	--	--	8 in. Chinese elm
OUI-TW28	16.5	07/30/03	146	--	--	--	--	8 in. Chinese elm
OUI-TW28	16.5	07/30/03	545	--	--	--	--	8 in. Chinese elm
Trees sampled near the former dry cleaning facility								
OUI-DF101	3	01/31/02	<0.8	<0.8	<10	<0.8	0.37	10 in. Boxelder
OUI-DF102	3	01/31/02	<.8	<.8	<10	<.8	.25	20 in. Chinese elm
OUI-DF103	3	01/31/02	<.8	<.8	<10	<.8	<.8	8 in. Chinese elm
OUI-DF104	3	01/31/02	<.8	.73	<10	<.8	<.8	8 in. Chinese elm
OUI-DF105	3	01/31/02	<.8	<.8	<10	<.8	1.6	Composite, 16 in. Chinese elm, 6 in. Redbud

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003—Continued

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft, feet; DS, downstream]

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
Poplar tree cuttings planted adjacent to Front Street building								
OU1-SAP-GS01	0.20833	10/22/02	80.1	<0.8	<10	<0.8	<0.8	Potting soil bag, Poplar sapling, SO side
OU1-SAP-GS01	1	10/22/02	<.8	<.8	<10	<.8	<.8	Potting soil bag, Poplar sapling, leaves
OU1-SAP-GS01	-.2	10/22/02	98.1	<.8	<10	<.8	<.8	Potting soil bag, Poplar sapling
OU1-SAP-GS02	.20833	10/22/02	<.8	<.8	<10	<.8	<.8	Poplar sapling, SO side
OU1-SAP-GS02	1	10/22/02	<.8	<.8	<10	<.8	<.8	Poplar sapling, leaves
OU1-SAP-GS02	-.2	10/22/02	51.9	<.8	<10	<.8	<.8	Poplar sapling, shoot below ground
OU1-SAP-GS126	-.5	07/09/03	8.04	<.8	<10	<.8	<.8	Poplar sapling, shoot below ground
OU1-SAP-GS126	0	07/09/03	.07	<.8	<10	<.8	<.8	Poplar sapling, SO side
OU1-SAP-GS126	.5	07/09/03	<.8	<.8	<10	<.8	<.8	Poplar sapling, leaves
OU1-SAP-GS127	-.5	07/09/03	22.1	<.8	<10	<.8	<.8	Poplar sampling, adjacent to TW08
OU1-SAP-GS127	0	07/09/03	9.25	<.8	<10	<.8	<.8	Poplar sampling, adjacent to TW08
OU1-SAP-GS127	.5	07/09/03	<.8	<.8	<10	<.8	<.8	Poplar sampling, adjacent to TW08
Poplar tree cuttings planted in tributaries 500TB and 210TB								
OUX-500tb-GS1	0	07/16/03	0	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS1	.729	07/16/03	0	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS2	0	07/16/03	95.3	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS2	.729	07/16/03	6.8	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS3	0	07/16/03	136	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS3	0.729	07/16/03	16.3	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS4	0	07/16/03	176	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS4	.729	07/16/03	26.2	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS5	0	07/16/03	129	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS5	.729	07/16/03	14.7	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS6	0	07/16/03	137	--	--	--	--	Poplar cutting in 500TB
OUX-500tb-GS6	.729	07/16/03	9.6	--	--	--	--	Poplar cutting in 500TB
OU4-210tb-GS7	.729	07/16/03	26.2	--	--	--	--	Poplar cutting in 210TB
OU4-210tb-GS7	0	07/16/03	19.5	--	--	--	--	Poplar cutting in 210TB
OU4-210tb-GS7	-.44	07/16/03	8.2	--	--	--	--	Poplar cutting in 210TB
OU4-210tb-GS8	.729	07/16/03	35.8	--	--	--	--	Poplar cutting in 210TB
OU4-210tb-GS8	0	07/16/03	8.7	--	--	--	--	Poplar cutting in 210TB
OU4-210tb-GS8	-.44	07/16/03	3.5	--	--	--	--	Poplar cutting in 210TB

Table 2. Concentrations of tetrachloroethene (PCE) and other volatile organic compounds in tree-core samples collected from the Front Street site and former dry cleaning facility, 2000–2003—Continued

Tree identifier	Height above land surface (feet)	Date	PCE	TCE	cis-DCE	Benzene	Toluene	Comments
PCE concentrations in tributaries 500TB and 210TB								
OUX-500TB-2	0	06/30/03	90	--	--	--	--	Water from 500TB-2
OUX-500TB-2	0	07/16/03	76.4	--	--	--	--	Water from 500TB-2
OUX-500TB-2	0	07/16/03	84.1	--	--	--	--	Water from 500TB-2
OUX-500TB-2	0	07/16/03	64.1	--	--	--	--	Water from 500TB-2
OU4-210TB-C6	0	06/30/03	21.7	--	--	--	--	Water from 210TB-C6
OU4-210TB-C6	0	07/16/03	27.0	--	--	--	--	Water from 210TB-C6
OU4-210TB-C6	0	07/16/03	23.8	--	--	--	--	Water from 210TB-C6
OU4-210TB-C6	0	07/16/03	15.8	--	--	--	--	Water from 210TB-C6
Trees sampled along the bank of tributary 500TB								
OU2-GCS01	3	06/30/03	10.9	4.61	2.8 J	<0.8	<0.8	11 in. Willow at 500TB-2 on LB
OU2-GCS02	3	06/30/03	4.31	<.8	<10	<.8	<.8	5 in. Willow, RB 60ft DS 500TB-2
OUX-GCS01	3	06/30/03	<.8	--	--	--	--	11 in. Willow at 500TB-2 on LB
OUX-GCS02	3	06/30/03	<.8	--	--	--	--	5 in. Willow, RB 60ft DS 500TB-2
OUX-GCS01	3	07/09/03	.97	--	--	--	--	11 in. Willow at 500TB-2 on LB
OUX-GCS01	3	07/09/03	13.5	3.41	9.1 J	<0.8	2.15	11 in. Willow at 500TB-2 on LB
OUX-GCS03	3	07/09/03	<.8	--	--	--	--	Sycamore
OUX-GCS03	3	07/09/03	<.8	<.8	5.6 J	<.8	<.8	Sycamore
OUX-GCS04	3	07/09/03	<.8	--	--	--	--	Sycamore
OUX-GCS04	3	07/09/03	11.0	2.84	8.9 J	<.8	<.8	Sycamore
Soil samples from the former dry cleaning facility (concentrations in micrograms per kilogram)								
OU1-HSS01	2.00	02/08/02	<0.8	<0.8	27.3	<0.8	21.4	Soil sample
OU1-HSS02	1.00	02/08/02	<.8	<.8	<.8	<.8	20.2	Soil sample
OU1-HSS02	2.00	02/08/02	<.8	<.8	<.8	<.8	5.67	Soil sample
OU1-HSS03	1.00	02/08/02	<.8	<.8	<.8	<.8	.5	Soil sample
OU1-HSS03	2.00	02/08/02	<.8	<.8	<.8	<.8	.45 J	Soil sample
OU1-HSS04	1.00	02/08/02	.16 J	<.8	<.8	<.8	<.8	Soil sample
OU1-HSS03	3.00	02/08/02	<.8	<.8	<.8	<.8	1.5	Soil sample

[All concentrations in micrograms in headspace per kilogram of wet core; PCE, tetrachloroethene; TCE, trichloroethene; cis-DCE, cis-1,2-dichloroethene; <, less than; in., trunk diameter in inches; J, estimated concentration below the method reporting limit; NW, northwest; SO, south; NE, northeast; NO, north; SW, southwest; --, no data; LB, left bank; RB, right bank; ft, feet; DS, downstream]



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