Direct Transpiration and Naphthalene Uptake Rates for a Hybrid Poplar Based Phytoremediation System

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ABSTRACT

Direct transpiration rates and plant uptake of naphthalene by a hybrid poplar phytoremediation system located in Oneida, Tennessee were determined using hydrologic and groundwater concentration data. Water table recession analysis techniques were employed to determine direct transpiration rates from the saturated zone of the shallow, unconfined aquifer underlying the site. Direct transpiration rates varied over the growing season (late March to mid-October), with a maximum and mean daily direct transpiration of 0.0100 and 0.0048 feet/day, respectively. During 2004, the maximum direct transpiration rate was observed in May, and rates declined starting in June due to an associated decline in the water table. A technique was developed to estimate the volumetric transpiration rate of each tree based on the breast-height diameters and seasonally variable direct transpiration rates. During peak transpiration, the larger trees at the study site were estimated to directly transpire 4 to 13 gallons per day per tree. Plant uptake rates of naphthalene were estimated by superimposing spatial data (volumetric transpiration rates and naphthalene concentration in groundwater). The mass loss rate of naphthalene from the aquifer as a result of plant uptake during July 2004 was 335 mg/day which only represents 0.117% of the aqueous mass plume. Monthly groundwater profiles showed a decrease of the saturated thickness beneath the system of hybrid poplars between the dormant and active season. This study suggests direct transpiration rates and plant uptake of naphthalene are dependent on variables including climatic parameters, magnitude of the saturated thickness, and the concentration of naphthalene in groundwater.

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1 INTRODUCTION

1.1 Phytoremediation Overview

Remediation of contaminated soil and groundwater has undergone significant improvements since the introduction of conventional pump-and-treat. Phytoremediation is an innovative in-situ technique that utilizes plants for enhancing the attenuation rate of contaminated soil and groundwater (U.S. EPA, 2000). An array of mechanisms is employed to remediate various contaminants from subsurface media depending on the contamination and type of plants (Pivetz, 2001).

Studies indicate that phytoremediation influences the fate of contaminants found in soil, sediments, and groundwater by degradation, removal, and immobilization (Pivetz, 2001). Though effective, these remediation mechanisms tend to occur simultaneously, making them difficult to differentiate. While immobilization (removing the means for transport) can in part be accomplished utilizing plants which reduce recharge via interception, hydraulic control can best be accomplished by phreatophytic consumption because it slows the migration of contaminant plumes by providing a sink for groundwater flow (U.S. EPA, 2000). For a phytoremediation system, phreatophytic consumption use is the single-most influential factor on hydraulic control (Vose et al, 2003).

Plant water use is driven by evaporative loss, or evapotranspiration. Evapotranspiration from a land area can be divided into two components:
1) transpiration of water from the subsurface through plants leaves, and 2) the evaporation of water from soils and water bodies (Viessman & Lewis, 2003). Transpiration is the uptake of water by plants through soil, roots, and stems followed by the subsequent release to the atmosphere via evaporation across the leaf surface (Noggle, 1976). Water loss from an aquifer is best described by direct transpiration since it does not include water loss from the land surface. Direct transpiration refers to transpiration which removes groundwater directly from the saturated zone of an aquifer. Success of a phytoremediation system is dependent on transpiration because plants must consume enough groundwater to influence the fate of subsurface contaminants (Vose et al, 2003).

Transpiration rates are influenced by a variety of factors including climate, soil-water availability, and time of season (Hopkins et al, 2004). Transpiration is a seasonal process which occurs during spring and summer, or when the trees are leafed (Fitter et al, 1981). During fall and winter trees are not active and the transpiration process becomes dormant.

Since plant water use is significant to the success of a phytoremediation system to control groundwater flow, it is desirable to utilize a plant that has a large capacity for transpiration. Due to their high water use, it has become a common practice to use phreatophytes for phytoremediation. Phreatophytes are deep-rooted plants that seek water in the saturated zone (Jordahl et al, 1996). A commonly used phreatophyte is the hybrid poplar. Long-lived, perennial, and tolerant, hybrid poplars utilize copious amounts of groundwater drawing from aquifers at depths upwards of fifteen feet (Freeze & Cherry, 1979; Viessman & Lewis, 2003). A stand of poplar trees can create a significant groundwater sink during the growing season, with the potential of inducing groundwater flow towards the center of the poplar grove (Schneider, 2000).

Plant uptake is another important phytoremediation mechanism which refers to the ability of plants to remove contaminants from an aquifer through transpiration. The fate of contaminants interacting with a plant is dependent on the physical properties of the contaminant and the type of plant. For instance, phytoextraction refers to the uptake and accumulation of metals by plants via transpiration (Schnoor, 2002). Phytovolatilization refers to the transport of volatile organic compounds (VOCs) from the subsurface to the atmosphere via plant transpiration (U.S. EPA, 2000). Studies show that hybrid poplars are capable of removing VOCs from contaminated aquifers and discharging them through tree tissue into the atmosphere as a gaseous product (Schneider, 2000). The uptake and subsequent metabolism of organic contaminants from the subsurface is known as phytotransformation (Schnoor, 2002).

A phytoremediation project at Oneida, Tennessee has been underway for several years. At its inception in 1997, 1,036 hybrid poplar trees were planted as a long-term solution to hydraulically contain and remediate creosote-based contaminants in-situ. Groundwater level monitoring at the Oneida site has provided hydrologic data indicating the poplar trees directly transpire measurable amounts of water from the saturated zone of the underlying shallow, unconfined aquifer (Panhorst, 2000). Recent tree tissue analysis in conjunction with measurement of PAH concentrations in groundwater indicates poplar trees are extracting and volatilizing contaminant mass from the subsurface (R. Anderson, personal communication). The combination of these data indicates the phytoremediation system at Oneida influences both plume migration and reduction of polycyclic aromatic hydrocarbon (PAH) concentrations (Widdowson et al, in press).

1.2 Objectives

Two principal remedial goals at the Oneida phytoremediation site were to use the system of poplar trees to hydraulically control the contaminant plume in the shallow aquifer and to reduce the concentration of PAH compounds. The objectives of this study were: 1) quantify the rate of groundwater directly transpired from the saturated zone (T_{DT}) using hydrologic data, 2) estimate volumetric direct transpiration rates across the site on a per tree basis (Q^{T}_{DT}), and 3) quantify the naphthalene mass removal rate by the system of poplar trees.

1.3 Approach

The quantification of direct transpiration from the saturated zone of the aquifer underlying the Oneida site is based on long-term hydrological and groundwater level monitoring. Utilizing continuous water table elevation data within the phytoremediation system, groundwater recession trends are established and used to calculate direct transpiration via two techniques: 1) Groundwater Recession Comparison method and (2) White’s Equation. Each of these methods results in a rate of direct transpiration in units of feet/day.

Upon calculating direct transpiration in feet/day, the values are converted to volumetric flowrate by multiplying by the land surface area. This value is then distributed among the poplar trees growing within the land area, taking into account tree mass. This in turn provides an estimate of the volumetric rate of direct transpiration on a per tree basis.

The final step of this analysis is to spatially correlate the per tree volumetric transpiration rates to concentration data of the contaminated plume. The volumetric rate of direct transpiration for each tree is then multiplied by the local naphthalene concentration and the Transpiration Stream Concentration Factor (TSCF) to quantify the mass of contaminants leaving the aquifer via plant uptake.

2 LITERATURE REVIEW

2.1 Transpiration and Evapotranspiration

Transpiration is the evaporation of water from plant leaves (Fitter et al, 1981). Transpiration primarily occurs at the leaf surface while the stomata are open for the passage for CO_2 and O_2 during photosynthesis (Noggle, 1976). Also termed ‘active transpiration,’ it is the component of water lost from the subsurface through live plants (Mieresonne et al, 1999). Transpiration is influenced by the following factors: climate (precipitation, temperature, vapor pressure, solar radiation, wind speed, humidity, and barometric pressure), soil water availability, groundwater depth, leaf area, stomatal functions, root mass and distribution, and aquifer parameters (Hopkins et al, 2004).

Transpiration is measured by both direct and indirect methods. Sap flow analysis, widely considered a direct measurement of tree transpiration, is a determination of the rate of water movement through trees from both the vadose zone and the saturated zone. Sap flow is estimated by measuring the amount of heat which is transferred vertically in the trees xylem due to upward water flow and multiplying the measured rate by some scaling factor to determine the rate of transpiration (Kjelgaard, 1996). Single tree quantifications of transpiration are extrapolated to estimate the water use of entire tree stands (Schiller et al, 2001).

An older, less direct method for estimating transpiration resulted from water table fluctuation analysis conducted by W.N. White in the early 1930s. Located in the arid Escalante Valley of Utah, White monitored ground water levels and observed diurnal water table fluctuations. White observed that during the day the water table fell while after sunset the water table would begin to get higher again until the next morning when the sun began to rise. Overall, White observed that the net change in groundwater levels were lower than the day before. White attributed this diurnal pattern and water loss to phreatophytic consumption. He concluded that during the day, when the tree stomata were open, the water table fell. At night, when the stomata closed, the process of transpiration halted until the next day. Analyzing the water table level data, White developed an equation for estimating transpiration based on the slopes of diurnal water table fluctuations (White, 1932).

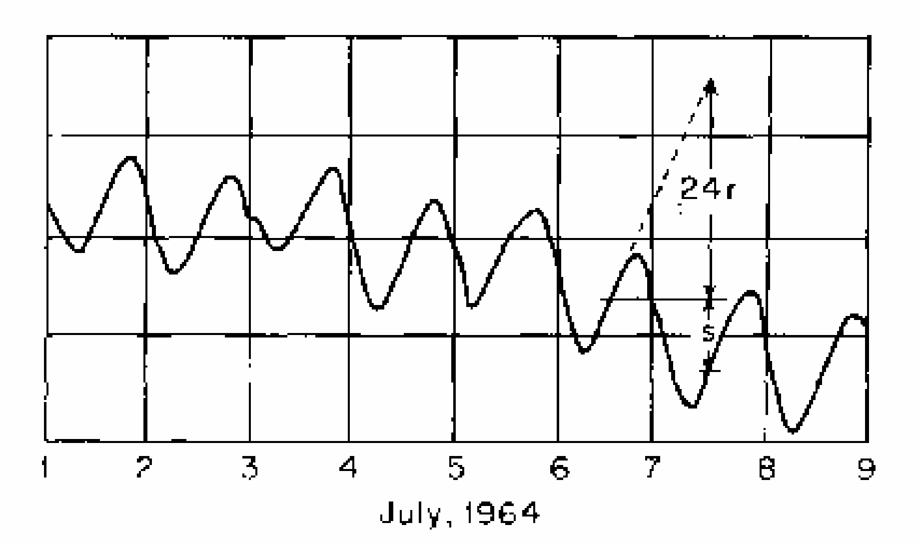


Figure 2.1 Example of diurnal fluctuations in shallow observation wells in Canada (Freeze & Cherry, 1979 p.231).

White explained his equation, “The total quantity of groundwater withdrawn by transpiration and evaporation during the 24-hour period can then be determined by the formula $q = y(24r \pm s)$, in which q is the depth of water withdrawn per 24 hours, in inches, y is the specific yield of the soil in which the daily fluctuation of the water table takes place, r is the hourly rate of rise of the water table from midnight to 4 a.m., in inches, and s is the net fall or rise of the water table during the 24-hour period, in inches. In field experiments the quantities on the right hand side of the formula except specific yield can be readily determined from the automatic records of water-table fluctuation” (1932). White also researched the effect of direct evaporation on water table decline. He concluded that when the depth of the water table was beyond two feet from the land surface, evaporative influence on the water table was almost negligible (White, W.N., 1932). Therefore, according to White, diurnal fluctuations of the water table which is greater than 2 feet below the land surface can be attributed to transpiration.

Transpiration is a seasonal process which is dependent on the condition of the plant and meteorological conditions (Fitter et al, 1981). White (1932) observed that diurnal water fluctuations began at first leaf in the spring and declined with defoliation until all leaves had eventually dropped. The start and end of a typical growing season is dependent on geographic location, elevation, and weather patterns.

Evapotranspiration (ET) is the combination of evaporation from soil surfaces, evaporation of intercepted precipitation, and transpiration from the soil by plants (Freeze and Cherry, 1979). Many researchers object to the term evapotranspiration and refer to all processes of vapor transfer to the atmosphere from all surfaces as evaporation (Monteith, 1973). Evapotranspiration is driven by the same parameters as transpiration; however ET is used to describe the bulk amount of water evaporated from an area which includes both bare soils and vegetation. In a water budget, ET typically has units of length (vertical drawdown) per time and generally encompasses a large land area.

Evapotranspiration is measured by a variety of methods which utilize various spatial and meteorological parameters. The Penman-Monteith (PM) method is an energy balance based on vapor pressure, net radiation, air temperature and soil heat flux (Monteith, 1965). The PM method is a popular way for determining ET, though parameters are often estimated. The eddy covariance (EC) method is used to directly measure fluxes between the land surface and the atmospheric surface layer whose differences can be used to estimate values of evapotranspiration representing large areas (Garratt, 1984). Moisture fluxes within the lower reaches of the atmosphere are calculated and used to estimate ET. The Thornthwaite Method (TM) is based on air temperature, latitude, and season (Thornthwaite, 1948). This method emphasizes meteorological controls and ignores soil moisture changes. Since the availability of soil water is unaccounted for, the Thornthwaite method results in an estimation of the potential evapotranspiration (PET) of a large area.

Evapotranspiration measurement methods do not provide or take into account source water (aka: groundwater). Since trees often utilize rainwater stored in the vadose zone, measured evapotranspiration rates do not correlate well with fluctuations of groundwater levels (Davis and Peck, 1986; Cramer, 1999). For this reason, transpiration is the most applicable process for determining the effectiveness of a phytoremediation system since the plants must transpire enough water from the subsurface to uptake contaminants (Vose et al, 2003). The quantification of transpiration requires comprehensive evaluation of site specific data pertaining to groundwater fluctuations, climate, and soil water availability (Vose et al, 2003).

2.2 Water Table Fluctuations in an Unconfined Aquifer

Groundwater level monitoring is an important component of many hydrologic investigations. Fluctuations observed in wells and piezometers are good indicators of recharge, yield, and consumptive water use, but may be skewed by other outside influences (air entrapment, bank storage near streams, tidal effects near oceans, pumping, artificial recharge, geotechnical drainage) (Freeze and Cherry, 1979). The elevation of the groundwater table at a particular location rises and falls for a variety of reasons including recharge, evapotranspiration, barometric pressure influences, and air entrapment. The two most significant causes of water table fluctuations are recharge and evapotranspiration (Freeze and Cherry, 1979). Both evapotranspiration and recharge influence the water table on a short (<24 hrs) and long term (>24 hrs) basis (Freeze and Cherry, 1979).

2.2.1 Water Table Fluctuation Due to Recharge & Air Entrapment

Precipitation across a land surface results in the recharge of underlying aquifers. Rain infiltrates the surface and percolates downwards through the vadose zone until it reaches the saturated zone. This effectively increases in the level of the water table.

During or just after a significantly heavy rain, uncharacteristic fluctuations of the water table in shallow, unconfined aquifers have been observed which are considered beyond reasonable for the particular recharge event (Freeze and Cherry, 1979). Sudden extreme increases of the water table level are typically followed by an equally dramatic decline of the water table which is beyond what is reasonable for drainage. This phenomenon has been attributed to air entrapment and pressure buildup. During or after a heavy rain, the uppermost portion of the vadose zone becomes saturated. As the layer of water percolates downward towards the capillary fringe, the pressure of the air voids between the traveling water front and the water table increases beyond atmospheric. This increase of pressure pushes on the saturated zone and forces the water into the void spaces which were previously unsaturated. The effect is a large, short-lived increase of the water table level. Eventually, the air dissipates beyond the perimeter of the advancing water front, the pressure of the subsurface air returns to atmospheric, and the water table falls back to what is considered “normal” for the recharge event (Freeze and Cherry, 1979).

2.2.2 Water Table Fluctuations Due to Evapotranspiration/Transpiration

Both driven by some of the same climatological factors, transpiration and evapotranspiration are closely related. Both are influenced by vapor pressure, temperature, solar radiation, wind, and humidity. With regard to groundwater though, transpiration and evapotranspiration differ. Transpiration is the consumption of water found in the subsurface while evapotranspiration is the combination of transpiration and the evaporation from all surfaces including dead plants, bare soils, and water bodies. From a phytoremediation perspective, it is important to differentiate between transpiration and evapotranspiration because groundwater uptake is significant to the remediation of contaminated aquifers.

As previously mentioned, transpiration of groundwater by vegetation has been shown to influence levels of the water table (White, 1932). White observed water table declines during the day when the stomata of the overlying trees were open and groundwater recoveries at night when the stomata were closed. He concluded that transpiring vegetation had a significant influence on groundwater levels.

Evaporative loss from the soil surfaces is further diminished by the presence of vegetation. When the canopy of a forested area is full, the effects of wind and solar radiation on the land surface are buffered by the trees leaves. Therefore, when the land surface is covered with vegetation, transpiration becomes the principal mechanism driving the transfer of water from soil to air (Hillel, 1998).

With regard to the hydraulic control mechanism of a phytoremediation site, the effectiveness of a phytoremediation system can be determined by understanding the influence of water losses caused by transpiration. Since evaporation does not include a significant amount of groundwater, transpiration becomes the most influential factor on water loss from an aquifer underlying a fully developed phytoremediation system (Vose et al, 2000).

2.2.3 Water Table Fluctuations Due to Atmospheric Pressure Changes

Barometric pressure is defined as atmospheric pressure exerted on a surface of unit area caused by the weight of the air column above, normally between 950 - 1050 hPa at sea level. It indicates the presence and movement of weather patterns and affects many physical measurements.

Peck (1960) described the effects of barometric pressure on the water levels in observation wells of unconfined aquifers with shallow water tables. Groundwater level fluctuations were attributed to the presence of entrapped air both in the capillary fringe and below the water table, with an increase in barometric pressure causing a decrease in water levels (Hare et al, 1997). When barometric pressure increases, the pressure exerted on the air voids in the subsurface causes a decrease in volume. As a result, more space becomes available for water to occupy and the water table level decreases. Conversely, when barometric pressure decreases, the air in the subsurface expands and occupies more space. This decrease in space for water effectively causes the water table to rise. Freeze & Cherry (1979) reported that only small fluctuations in the water table have been observed in unconfined aquifers.

2.3 Hybrid Poplar Trees and Water Use

Hybrid poplar trees are phreatophytes which are deep rooted plants that seek water from the saturated zone (Jordahl et al, 1996). Hybrid poplars found in the southeastern United States are typically a cross between *Populus deltoides* and *Populus trichocarpa*. Known for high water use, fast-growing nature, and tolerance of adverse conditions, hybrid poplar trees thrive in moist, wet soils in temperate climates (Meiresonne, 1999).

Figure 2.2 Hybrid poplar tree, *Populus deltoides x Populus trichocarpa*

New treatment technologies such as phytoremediation have initiated the use of hybrid poplar trees as mechanisms which are able to move large quantities of water from the saturated zone to the atmosphere (U.S. EPA, 2000). At a phytoremediation site in Aberdeen, Maryland, data analysis concluded that hybrid poplar trees used to hydraulically control the migration of TCE contaminated groundwater transpired an average of 1.4 to 10.8 gal/day/tree during the growing season (Schneider et al, 2003). In Flanders, Belgium sap flow studies were conducted which indicated that hybrid poplars were directly transpiring (recession of the water table) a mean value of 0.0049 ft/day (Meiresonne et al, 1999). In another phytoremediation site in Ogden, Utah, 3-year old hybrid poplar trees were estimated to consume an average of 2.8 gallons/day-tree (Ferro, et al, 2001).

The rate of transpiration in most species of vegetation is determined by soil water availability, climatic demand, physiological response mechanisms, and environmental conditions (Calder, 1993). Research performed by J.M. Mahoney at the University of Lethbridge indicates a relationship between depth to groundwater and hybrid poplar performance via a correlation between rapid water table decline and hybrid poplar stress (1991). The study concluded that as the distance between the root mass and the water table increases, the stress inflicted on the tree increases proportionally. Examples of stress included reduction of transpiration, decreased leaf number, and overall decline of plant health (Mahoney, 1991). This study suggests that even if meteorological conditions are optimal for the maximization of potential transpiration, the amount of water actually transpired will be lower than expected due to stress inflicted by water table decline.

2.4 Relationship between Transpiration and Tree Size

It stands to reason that the larger the plant, the more water it transpires. In general, tree size is determined by trunk diameter, height, and leaf area. For a given stand of trees, the variation of transpiration between individual trees can be attributed to differences in the leaf area (Vose et al, 2003). Since transpiration occurs at the surface of the leaf, and the amount of water transpired increases with the surface area of a leaf, overall leaf area of a tree is an important factor to consider when estimating transpiration. The problem with this parameter is the extreme difficulty of measurement. In order to quantify the leaf surface area of a particular tree, the tree must be cut down and the leaves harvested for measurement (Zhang et al, 1997). Though accurate, this method is neither convenient nor efficient with regard to a long-term phytoremediation system.

According to Vose et al, much of the variation in transpiration rates of poplar stands can also be attributed to tree diameter because larger trees have greater sapwood area which results in more sap flow (2003). In the field of forestry the location on a tree where the diameter is measured is known as “diameter at breast height (DBH).” More precisely, “breast height” is equal to 1.37 meters above the land surface on the uphill side of the slope (Husch et al, 1993). A study in Australia concluded that the DBH correlated with transpiration, sap flow area, and leaf area (Eamus et al, 2000). In India, research regarding transpiration from Eucalyptus plantations indicated that tree transpiration rate is proportional to the square of the DBH (Calder, 1993). In addition, the Eucalyptus study concluded that “for three of the four sites, encompassing ages ranging from 2 to 5 years, the simple relationship between daily transpiration rate and cross sectional area appears to hold under non-soil moisture stress conditions and thus provides a simple rule for estimating transpiration losses, independent of meteorological measurements” (Calder, 1993).

2.5 Phytoremediation and Plant Uptake of Contaminants

In the late 1990s, Burken and Schnoor conducted laboratory studies on the uptake of a variety of organic contaminants from water by hybrid poplar trees (1998). Hybrid poplar cuttings were grown hydroponically in waters with known concentrations of volatile organic chemicals. It was concluded from the studies that direct uptake of contaminants is dependent on transpiration rate, efficiency, and the contaminant concentration (Burken and Schnoor, 1997). This research yielded a Transpiration Stream Concentration Factor (TSCF) equation for hybrid poplar cutting.

The "TSCF is a dimensionless ratio between the concentration of chemical in the transpiration stream of the plant to the concentration in soil water" (Schnoor, 2002). The TSCF is dependent on the octanol-water coefficient of the chemical compound found in the soil water. If this value is too low, the compound will not pass through the root surface. In contrast, if the octanol-water coefficient is too high, the compound will not partition in to the xylem of the tree. For a phytoremediation system, the TSCF may be applied to contaminant concentration data and transpiration rates to determine the mass of contaminant being removed by the system. As reported by Schnoor, the equation is as follows:

$$U = (TSCF)\,(T)\,(C)$$

Where: U = rate of contaminant uptake (mg/day),
TSCF = efficiency of uptake (unitless),
T = Transpiration rate (L/day),
C = soil water concentration of contaminant (mg/L).

The success of a phytoremediation site is driven by the effectiveness of methods which aid the removal of contaminants from the subsurface. Driven by plant water use, phytovolatilization is the uptake and transpiration of a contaminant by a plant. During the active season, growing trees consume groundwater which may contain significant amounts of dissolved contaminants (Schneider et al, 2003). As a result of the transpiration process, contaminants or modified forms of the contaminant are volatilized into the atmosphere (U.S. EPA, 2000). The loss of contaminants from the subsurface through trees can occur through trunk and stem tissue as well as the leaf interface.

Phytovolatilization has mainly been applied to contaminated groundwater, though has recently been applied to wastewaters, sludges, and sediments (U.S. EPA, 2000). The measurement of contaminants emanating from tree tissue is usually performed by first capturing contaminant mass in a Tedlar^{TM} bag which is sealed around either the trunk or stem of a plant. At a contaminated site in Aberdeen, Maryland, “Trees tissue and transpiration gas sampling confirm the poplar trees are withdrawing contaminant mass from the aquifer” (Schneider et al, 2003). Using known contaminant concentration data, per tree transpiration rates, and TSCF specific to both plant and chemical, the rate of contaminant uptake from a system may be determined (Schnoor, 2002). Ultimately, by evaluating the rate at which contaminants are being removed from a contaminated aquifer by specific mechanisms, the effectiveness of a phytoremediation system may be determined.

3 SITE DESCRIPTION

3.1 Site History

Located on the Cumberland Plateau in Scott County, the Town of Oneida is a small, rural municipality in north central Tennessee. Since the 1800s, the project site has been occupied by a railroad yard owned by various corporations. In the 1950s, the Tennessee Railway Company began operating a railroad tie treatment facility which underwent sporadic use until 1973 when the rail-yard was sold to the current owner. After purchasing the property, the current owner halted cross-tie treatment and removed the equipment from the facility.

During the operation of the treatment facility, personnel used earthen holding ponds for capturing used creosote. Over time, this dense non-aqueous phase liquid (DNAPL) infiltrated the subsurface and percolated downwards until settling on or near the shale confining layer located some ten to twelve feet below land surface.

The Oneida site (Figure 3.1) is bordered to the east by Pine Creek, a small creek usually containing low flows. In 1990, the Army Corps of Engineers discovered creosote seeping into Pine Creek. Creosote, a wood preservative used for treating railroad ties and telephone poles, consists of a mixture of chemicals including polycyclic aromatic hydrocarbons (PAHs). To prevent the creosote from further contaminating Pine Creek, an interception trench was constructed to divert contaminants to an oil-water separator where non-aqueous phase liquids could be removed.

A phytoremediation system was designed and implemented by ARCADIS Geraghty & Miller in conjunction with an upgrade to the interception trench as the remedial strategy for the Oneida site. In coordination with the current owner, Virginia Tech has been investigating the effectiveness of this strategy.

3.2 Site Hydrology & Hydrogeology

The temperate climate of Oneida, Tennessee deposits approximately 55 inches of precipitation per year. The largest amount of precipitation occurs during the winter and early spring while a secondary maximum tends to occur during late summer. Fall tends to be dry due to slow moving, high pressure systems. Summer can be characterized as relatively warm and humid, while winter as mild with relatively little snowfall. Table 3.1 summarizes the typical annual climate of the Oneida area.

Table 3.1 Average Climatological Observations for Oneida, TN

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days with precip.	12	11	13	11	11	11	12	10	8	8	10	11
Precipitation (in)	4.7	4.2	5.5	4.2	5.3	4.8	5	4.5	3.7	3.7	4.5	4.8
Average temp. (°F)	33.5	37	45.1	53.4	61.7	69.9	74	72.6	66.4	54.8	45.6	36.9
Wind speed (mph)	5.2	5.4	5.7	6	4.7	4.4	4.1	3.7	3.8	3.7	4.4	4.8
Morning humidity (%)	82	80	79	81	87	89	90	92	92	89	84	83
Afternoon humidity (%)	64	59	55	51	57	59	61	60	59	56	59	64
Sunshine (%)	40	47	53	63	64	65	64	63	61	61	49	40
Days clear of clouds	7	8	8	10	9	9	8	9	10	14	9	8
Partly cloudy days	7	6	7	7	9	10	12	11	9	7	7	6
Cloudy days	17	15	16	13	13	10	11	10	11	10	14	17
Snowfall (in)	3.4	3.2	1.5	0.2	0	0	0	0	0	0	0.4	1.8

The Oneida phytoremediation site is underlain by a shallow, unconfined aquifer with an east-southeast flow direction towards Pine Creek. The aquifer is characterized from top-to-bottom by three layers: 1) Approximately 2-3 feet of loam with coal and gravel, 2) 5-6 feet of silty clay, and 3) 4-6 feet of silty sand. The depth to the shale confining layer ranges from 10 to 12 feet below land surface and has a variable saturated thickness. In the summer of 1999, a slug test was conducted to determine the hydraulic conductivity of the aquifer. The result of the slug test by Panhorst (2000) in 1999 yielded a hydraulic conductivity of 0.20-0.23 feet/day, though a model calibrated by Panhorst (2000) yielded hydraulic conductivities of 4 feet/day and 8 feet/day, respectively. Corack (2003) also developed a model for the Oneida site. Corack's model determined hydraulic conductivities for specific areas within and around the Oneida phytoremediation site. For the area which encloses the system of trees, Corack (2003) determined the hydraulic conductivity was 20 feet/day. The specific yield (S_Y) of the sandy-clay aquifer is estimated to be 0.1 (Panhorst, 2000).

The level of the water table within the unconfined aquifer at the Oneida site remains relatively high during the winter with a depth to water level ranging from 2-4 feet below land surface during the dormant season and 5-11 feet during the growing season. The growing season in northeastern Tennessee is roughly 150 days long.

3.3 Contaminant Location

Figure 3.1 illustrates the probable location of the original contaminant sources. Contamination of groundwater at the Oneida site resulted from the utilization of an earthen holding pond for spent creosote and possibly a leaking aboveground storage tank (AST). Over time, the creosote percolated into the subsurface and into the groundwater. Due to its dense nature, the DNAPL (creosote) is now located approximately 6 to12 inches above the bedrock within the silty sand layer. Over time the DNAPL source has spread and its chemical constituents are detected in groundwater samples at a variety of depths.

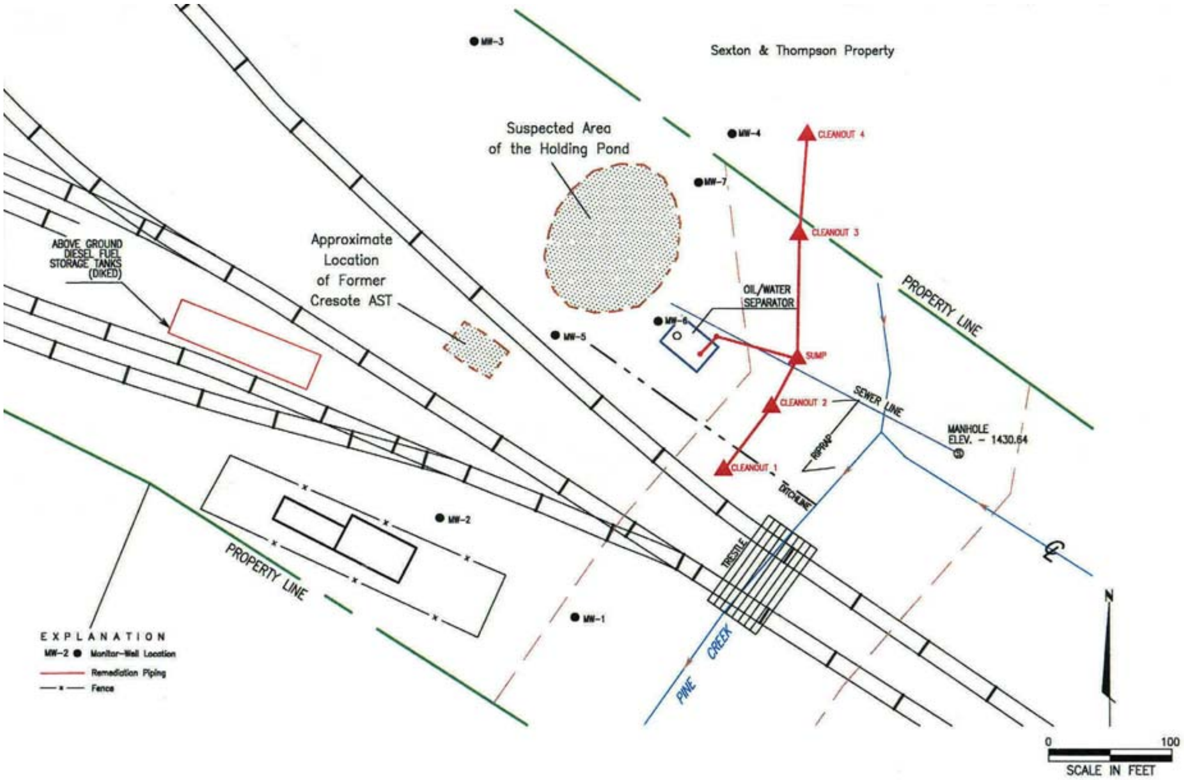


Figure 3.1 Oneida Tie Yard Site Plan (ARCADIS Geraghty & Miller, 2000).

4 MATERIALS AND METHODS

4.1 Phytoremediation System & Monitoring Location Overview

Monitoring of the Oneida phytoremediation site by Virginia Tech began in 1997. Since that time, numerous studies have been conducted which focused on hydrology, hydrogeology, and contaminant attenuation. The current study began at the beginning of 2004 and focuses on the analysis of hydrologic and contaminant concentration data to evaluate the effectiveness of the phytoremediation system with regard to plant uptake and hydraulic control. For the purpose of this study, hydrologic data were collected from March to October 2004. In conjunction with data collected intermittently from 1999-2003, hydrologic data were analyzed to determine the rate at which hybrid poplar trees directly transpire water from the saturated zone of the aquifer and to illustrate water table declines influenced by the phytoremediation system.

The phytoremediation system was implemented in the spring of 1997. The area planted was selected based on the historical location of the contaminant source (see Figure 3.1 in Site Description) and the direction of groundwater flow. The phytoremediation system can be broken into two primary plots. Located northwest of the oil-water separator, the first plot consists of eleven rows which are approximately parallel to groundwater flow. The second plot consists of nine rows which are approximately perpendicular to groundwater flow and are located east of the oil-water separator. Trees within rows are spaced at 3 feet on-center and the distance between rows is ten feet. Figure 4.1 illustrates the site plan and includes the locations of the trees as of June 2004. Located far northwest from the oil-water separator is an obvious area void of trees. This area was originally planted with poplar trees but their survival was limited due to the presence of a coal layer located just beneath the topsoil. The perimeter of the coal layer is also shown in Figure 4.1.

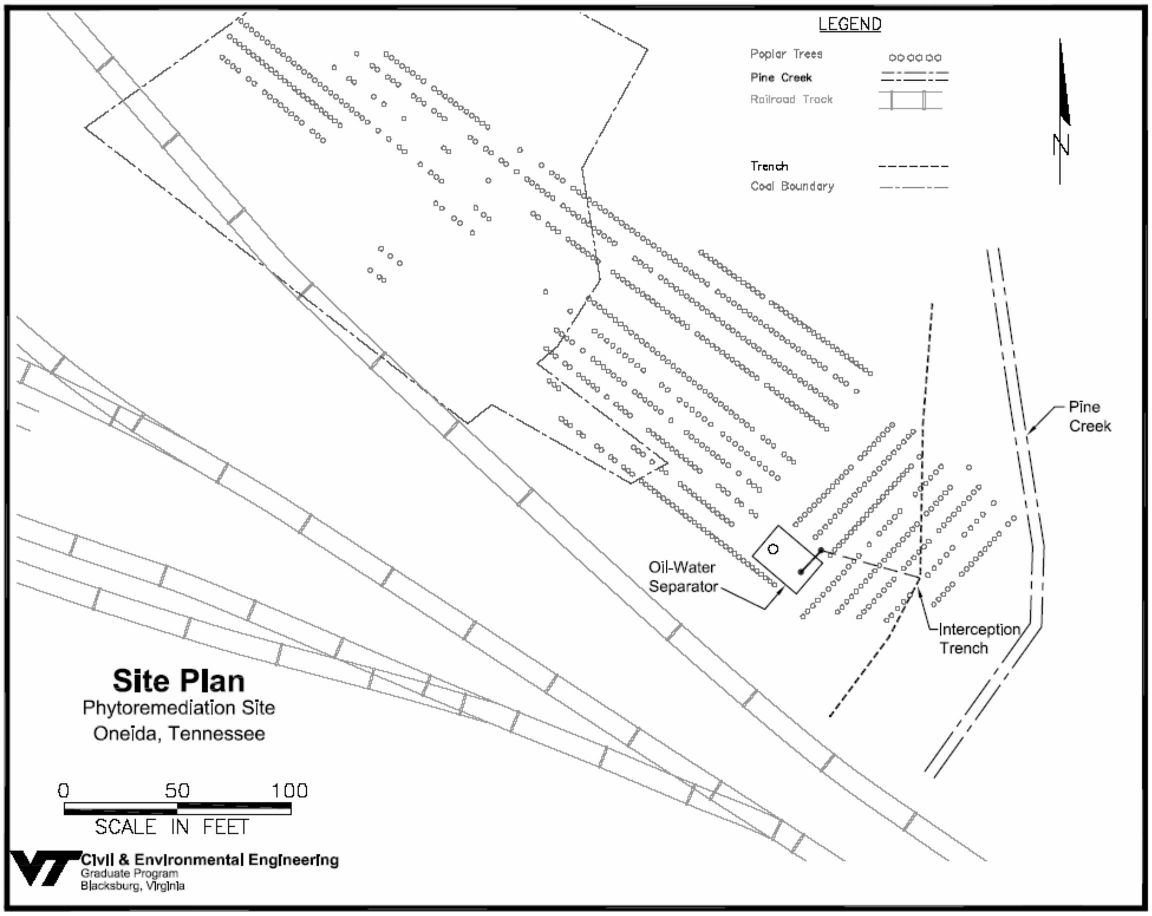


Figure 4.1 2004 Site Plan of Oneida phytoremediation site.

For the purpose of groundwater level monitoring there are 22 piezometers scattered across the site property. The piezometers are composed of 1-inch diameter PVC whose depths range from 6 to 11 feet below the land surface, each with a five-foot screened segment. There are 6 monitoring wells across the site, however only two (MW6 & MW3) have been utilized during the course of this study. For the measurement of groundwater contaminant concentration data, there are 30 multilevel samplers which are used to collect groundwater samples in up to eight ports spaced at 1-foot intervals beginning at a depth three feet below the land surface. In addition to groundwater monitoring, hydrologic data such as precipitation, temperature, and barometric pressure were also monitored using a weather station. Table 4.1 outlines the specifications of the piezometers and monitoring wells used during this study. Figure 4.2 illustrates the locations of piezometers (P), monitoring wells (MW), and the weather station.

Table 4.1 Piezometer and monitoring well construction summary.

Piezometer or Monitoring Well	TOC Elevation (feet)	Height Above Ground (feet)	Well Depth (feet)
P1	1436.79	1.00	6.79
P2	1436.96	1.92	9.94
P3	1435.98	1.75	9.87
P4	1435.04	0.25	9.74
P5	1434.65	1.50	9.63
P6	1434.17	0.17	9.43
P7	1432.77	0.25	9.77
P8	1432.14	1.33	NM
P9	1433.01	1.33	8.09
P10	1432.19	0.08	10.23
P11	1432.74	0.17	10.00
P12	1433.26	0.25	9.31
P13	1434.68	1.17	9.97
P14	1433.98	0.33	8.23
P15	1434.63	0.33	8.72
P16	1436.04	0.33	9.09
P17	1437.20	0.63	8.71
P20	1434.80	2.08	8.32
P21A	1434.37	*0.75*	5.64
P21B	1434.36	*0.75*	6.21
P21C	1434.37	*0.75*	8.36
P21D	1434.36	*0.75*	9.13
P22	1433.90	*2.50*	9.12
P25	*1425.57*	*2.00*	*11.43*
MW1	1433.64	NM	NM
MW2	1436.10	NM	NM
MW3	*1437.28*	NM	NM
MW6	1434.81	*2.50*	*15.19*

Italicized values are estimated

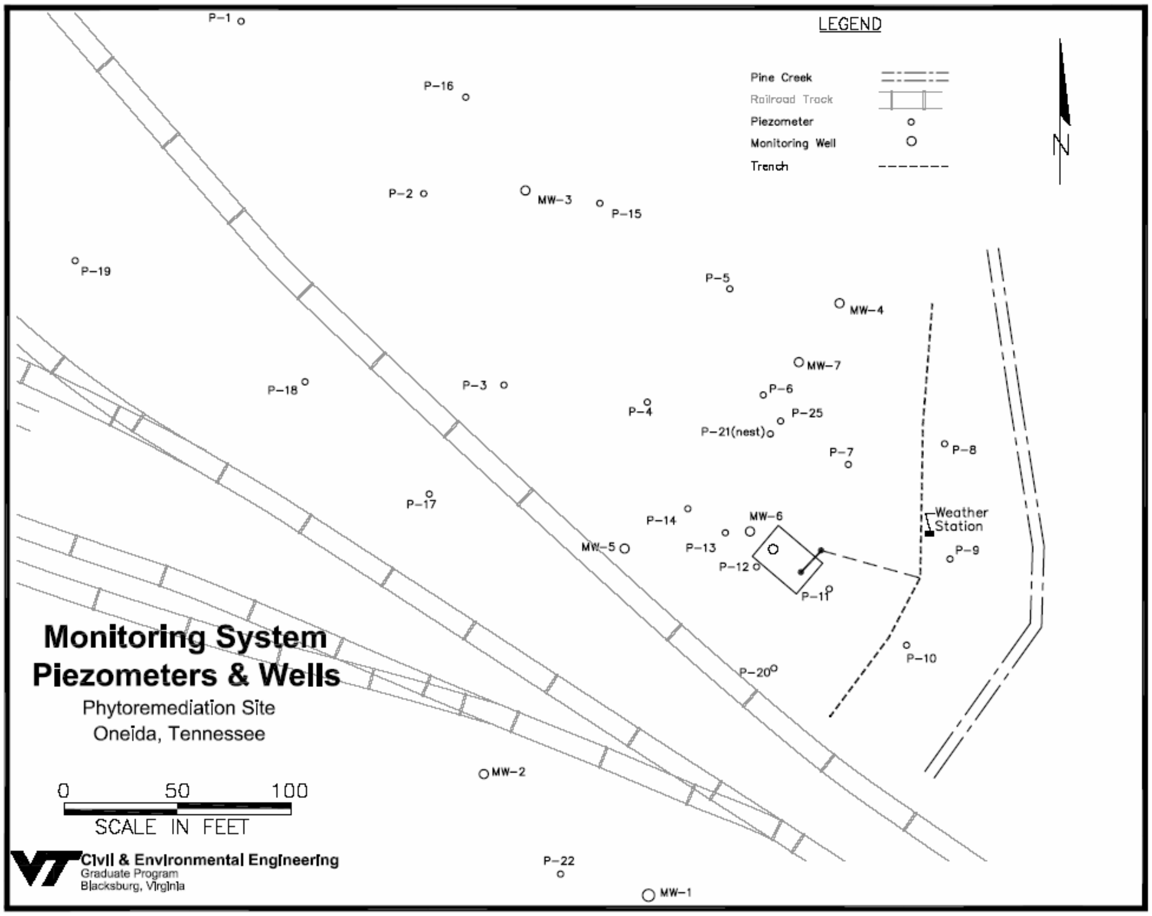


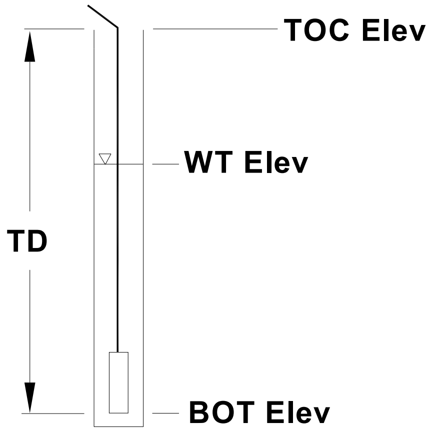
Figure 4.2 Monitoring System for Oneida Phytoremediation Site.

4.2 Field Methods

4.2.1 Groundwater Level Monitoring

Groundwater levels were monitored on a continuous basis and on a monthly basis at selected locations. Continuous groundwater levels were recorded by recording pressure transducers installed at three primary locations: 1) P4, 2) MW6, and 3) P25. These locations were chosen because of their relative location within the phytoremediation system and for their previous history of being used for this same purpose. Water level data had been recorded with these instruments at several locations intermittently between 1999 and 2003. Discrete water level measurements were recorded once a month from all available piezometers and monitoring well locations using a depth-to-water indicator fabricated by the Slope Indicator Company.

Continuous water level monitoring was accomplished utilizing Global Water (Global Water Instrumentation, Inc. Gold River, Ca. USA) Level Loggers. Loggers used for this study had an accuracy of ± 0.01 feet, though complications with sensor accuracy did arise during the monitoring period for this study. Global Water Level Loggers are battery powered (9-volt) and hold up to 6,000 data points before beginning to overwrite. All loggers used at the Oneida site during the 2004 monitoring period were set to record one value every half-hour in units of feet. Data from these loggers was downloaded in the field to a laptop computer and then converted to spreadsheets for data analysis. The value measured by the Global Water Level Logger is the amount of water in feet above the sensor which is located at the base of the transducer. This value is added to the known elevation of the base of the transducer which is calculated using the top of casing elevation for the particular piezometer.



where:

WT Elev = BOT Elev + Level Recorded by Transducer

and:

BOT Elev = TOC Elev - TD

Figure 4.3 Schematic of piezometer/monitoring well illustrating top of casing (TOC), water table (WT), base of transducer (BOT), transducer depth (TD).

Figure 4.3 illustrates the measurements used when installing a level logger for groundwater monitoring. During the original installation of piezometers and monitoring wells, the top of each casing was surveyed and its elevation recorded. This value was then used to calculate the various elevations (Table 4.2). When each Global Water Level

Logger was placed, each was positioned within a few inches from the bottom of the well. After placing the Global Water Level Logger in the piezometer, time was allotted to allow the water level in the particular piezometer to equalize. Upon equalization, the laptop was connected to the transducer to continuously monitor the height of the water column above the base of transducer (BOT). The depth to water from the TOC was then measured and added to the measured height of the water column to yield transducer depth (TD). The bottom of transducer elevation was recorded for P4, MW6, and P25 so that the elevation of the water table at each location could be monitored and compared over time.

Table 4.2 Installation measurements for each pressure transducer.

Valid Date Range	Well ID	Elev. TOC (ft)	Depth from TOC (ft)	Elev. BOC (ft)	Device Depth from TOC (ft)	Elev. Device (ft)
March 6, 2004 to August 9, 2004	MW6	1434.81	15.19	1419.62	11.72	1423.09
	P3	1435.98	9.87	1426.11	9.766	1426.21
	P4	1435.04	9.74	1425.3	9.01	1426.03
August 9, 2004 to October 8, 2004	P25	*1433.57*	9.40	*1424.17*	9.2	1424.37
	MW6	1434.81	15.19	1419.62	12.77	1422.04
	P4	1435.04	9.74	1425.3	9.01	1426.03

Italicized values are estimated.

The primary purpose of continuous groundwater level monitoring is to establish a temporal trend for the fluctuations of the water table by which direct transpiration rates are determined. As mentioned in Chapter 2, water table fluctuations result from a variety of phenomena which are often related to changes in the local weather. Ideally, continuous groundwater level monitoring would occur at all piezometers and monitoring well locations, however, due to the expensive nature of level loggers, discrete water level measurements are used to study the water level changes across the site. The purpose of monthly water level measurements at all monitoring locations (piezometers and wells) is that it provides an overall understanding of the water table elevation across the entire site area. Discrete water level measurements are the key component to creating groundwater contours which are used to calculate parameters such as hydraulic gradient and saturated thickness.

4.2.2 Hydrologic Monitoring

Local climate changes directly influence water table fluctuations. Precipitation leads to recharge while temperature, wind, and humidity affect evapotranspiration rates. Recharge to an aquifer and transpiration by the hybrid poplars directly affects the water table elevation. For this reason, weather monitoring has been on-going in conjunction with groundwater level monitoring. Weather monitoring first began in 2000 utilizing a Davis *Groweather*™ weather station which recorded values for temperature, barometric pressure, rainfall, wind speed and direction, humidity, solar radiation, and dew point. This station operated relatively continuously from November 2000 thru May 2003.

In March 2004, a new Davis *Vantage Pro*™ weather station was installed and has been running continuously recording hydrologic data every half-hour. The weather station is located on the southwestern side of the site and is illustrated in Figure 4.2. The primary purpose of this weather station was to record rainfall and barometric pressure so that it could be correlated with water table fluctuations.

4.2.3 Tree Growth Monitoring

Tree circumference data was recorded in 1998, 1999, and 2001 (Lawrence, 2000, Panhorst, 2000). Each tree on-site has been identified by row and number and each is spatially located with regard to monitoring devices and groundwater contamination. The identification of each tree is based on its row number and position within that row. The assignment of row numbers is illustrated in Figure 4.4. Tree circumference data were available in a spreadsheet.

For this study, the circumferences of the trees were measured in June 2004 at breast height using a soft tape measure and then converted to diameter at breast height (DBH). These data were then compared to previously recorded data to determine the number of surviving trees and the percent increase in growth. Due to the difficulty of measurement, the precise height of each tree was not recorded at this time.

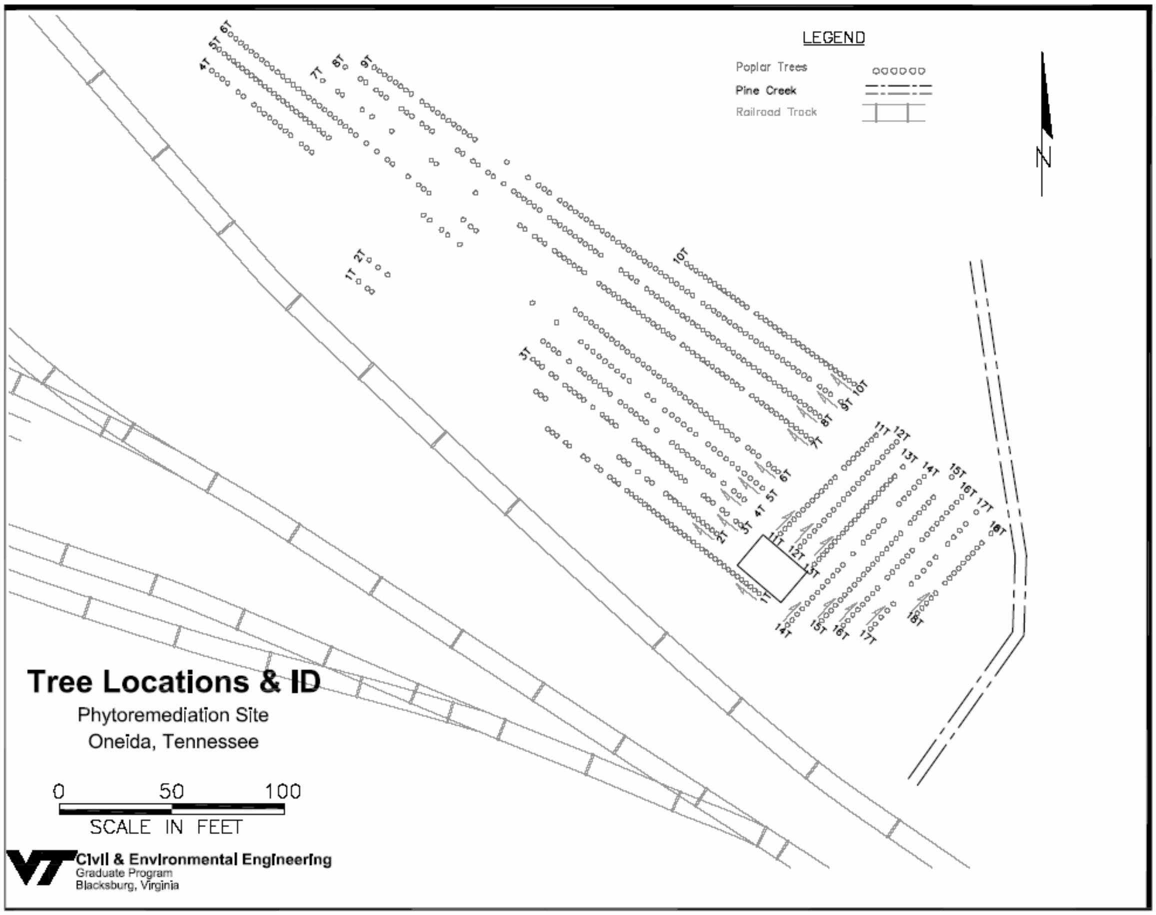


Figure 4.4 Locations and identification numbers of hybrid poplars as of June 2004.

4.3 Data Techniques to Quantify Transpiration Rates

The term ‘direct transpiration’ refers to water removed from the saturated zone by the transpiring poplar trees which results in a lowering of the water table over time. The rate of direct transpiration is determined by the analysis of water table fluctuations and supported by data from the weather station. The most important weather data considered in this analysis was rainfall because it was the source of recharge for the shallow unconfined aquifer which underlies the Oneida phytoremediation site. Two methods used to determine direct transpiration were: 1) Groundwater Recession Comparison method and 2) White’s Equation. Both methods utilize continuous water levels recorded by the Global Water Level Loggers at P4, P25, and MW6. Water level data and precipitation were analyzed in order to find water table recession durations which were not influenced by recharge.

4.3.1 Groundwater Recession Comparison Method

As previously mentioned, transpiration is a seasonal occurrence. Transpiration occurs during the ‘active season’ when the trees are leafed and undergoing photosynthesis. Transpiration becomes dormant during the late fall and winter months when the trees have no leaves. The groundwater recession comparison (GRC) method is based on the idea that at a specific location during periods of no recharge, the water table will recede at a rate which is dependent on the starting elevation of the water table at the beginning of the observation. More concisely, at a specific location the groundwater level will recede at approximately the same rate under similar circumstances. To illustrate this assumption, Figure 4.5 shows two water table recessions which occurred over a 48-hour duration in February 2001. Both recessions have nearly identical starting elevations. Each recession is fitted with a best-fit linear regression so the recession slope may be determined. In this example, the difference between the slopes is 0.009 feet which is less than the accuracy of the Global Water Level Logger (accurate up to ± 0.01 feet), so it assumed that the difference between recession slopes is negligible.

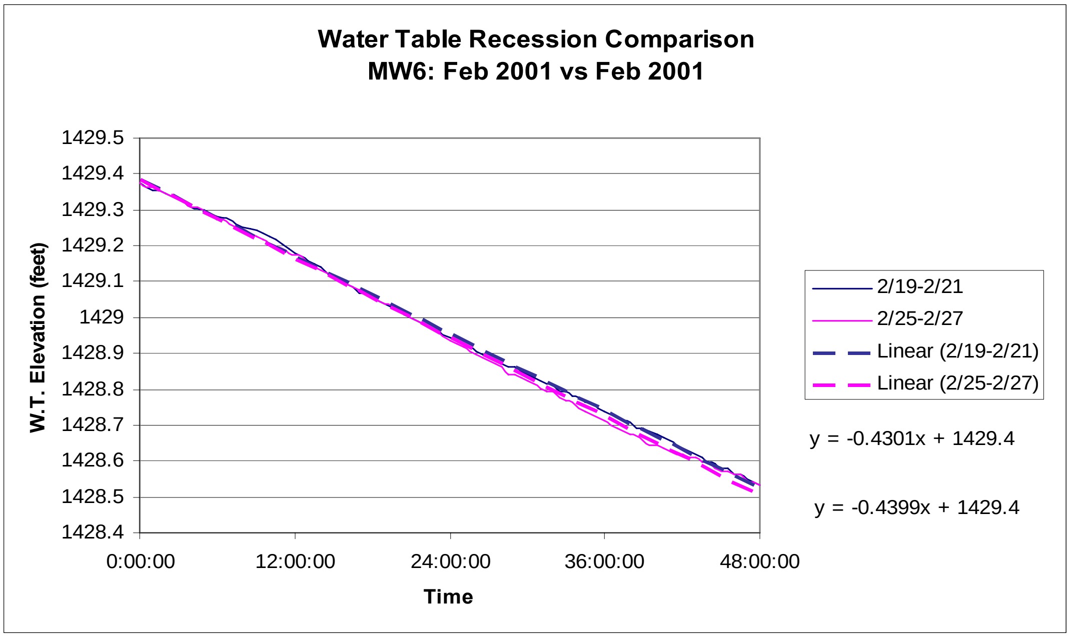


Figure 4.5 Example of water table recession comparison between two dormant season durations.

Rainfall is probably the most influential aspect of this analysis method. Recharge resulting from rainfall events causes upward fluctuations in the water table making recession comparisons nearly impossible. Since the GRC method is based on comparing two recessions which start from the same elevation, it is difficult to find long durations which are uninterrupted by rainfall. For this reason, most durations used in this study were approximately 72 hours. Under ideal conditions however, the recession durations would be longer.

With the observation that the water table recedes from similar starting elevations at the same rate during time periods when the trees are inactive, it can be assumed that the major difference between a recession rate measured during the active season and a recession rate measured during dormant season (from similar starting elevations) is due to evapotranspiration. If evaporation may be ruled out as a groundwater sink due to the average depth (>2') of the water table (White 1932, Freeze & Cherry 1979) and the amount of vegetation and full canopy created by the hybrid poplars (Hillel 1998), the primary difference between dormant and active season water table recessions can be attributed to direct transpiration. An example of dormant recession (January) versus an active recession (August) is shown in Figure 4.6. Note that each water table recession starts at an elevation roughly equal to 1427.07 feet.

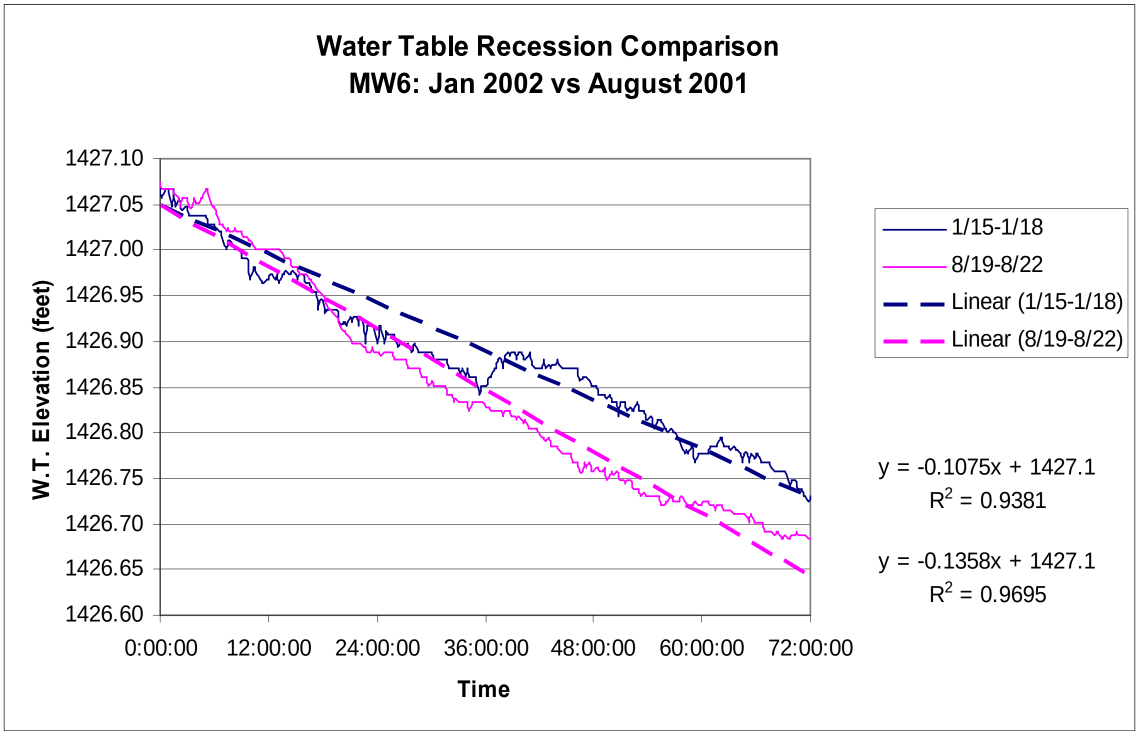


Figure 4.6 Groundwater Recession Comparison: dormant versus active durations.

Transpiration, T_{DT} (feet/day) is calculated by multiplying the difference between the absolute values of the linear regression slopes and multiplying by specific yield, $S_Y = 0.1$. The difference between the slopes in Figure 4.6 is 0.028; hence the direct transpiration rate during the period between 8/19 and 8/22 is approximately 0.0028 feet/day.

4.3.2 White's Equation

A second method for determining direct transpiration rates is White's Equation (White, 1932). This method focuses on diurnal water table fluctuations observed during the active season to determine the rate of transpiration. During the day, it is expected that the transpiring poplar trees surrounding the observation point create a groundwater sink causing the elevation of water table to decrease. At night, the water table is expected to recover in the absence of transpiration, so the water level in the piezometer temporarily (until the sun rises) increases. White's Equation uses this diurnal pattern to quantify evapotranspiration. Figure 4.7 illustrates a period in August 2004 where diurnal fluctuations were observed at the MW6 location.

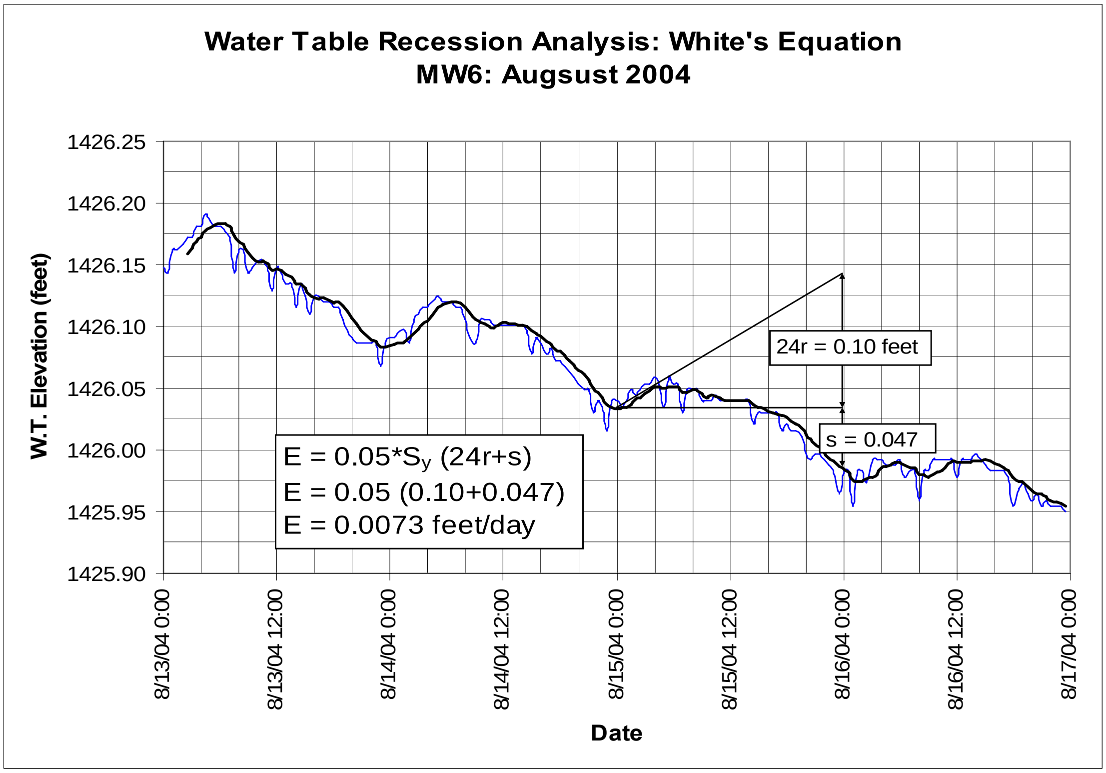


Figure 4.7 Example of White's Equation applied to August, 2004 MW6 data.

4.4 Determination of Direct Transpiration Flow Rates

Though useful, direct transpiration rates T_{DT} (feet/day) are somewhat arbitrary because they have no lateral boundaries. If it is assumed that the direct transpiration is due to water consumption by the poplar trees, then it is logical to limit the extents of these transpiration rates to the boundaries of the phytoremediation system. For this reason, direct transpiration rates are multiplied by a representative land area in order to calculate a volumetric direct transpiration rate, Q_{DT} (feet^3/day). However, rather than multiplying direct transpiration rates determined at each observation point by the total area of the site, the rates were multiplied by smaller, equally-sized representative areas surrounding each observation point. The primary reason for this was to account for variability of direct transpiration rates due to spatial variability regarding differences in the number of trees surrounding each point.

Based on the spacing of the tree rows, representative areas were created by dividing the site into a grid containing 10 x 10 foot cells. The grid, shown in Figure 4.8, was oriented with the direction of the tree rows and spatially located with regard to the contaminant plume. The grid was sized large enough to contain the contaminant plume and the trees which were available for contaminant uptake. The trees in the northwest portion of the site were left out of the grid because there is no evidence of contamination in that area.

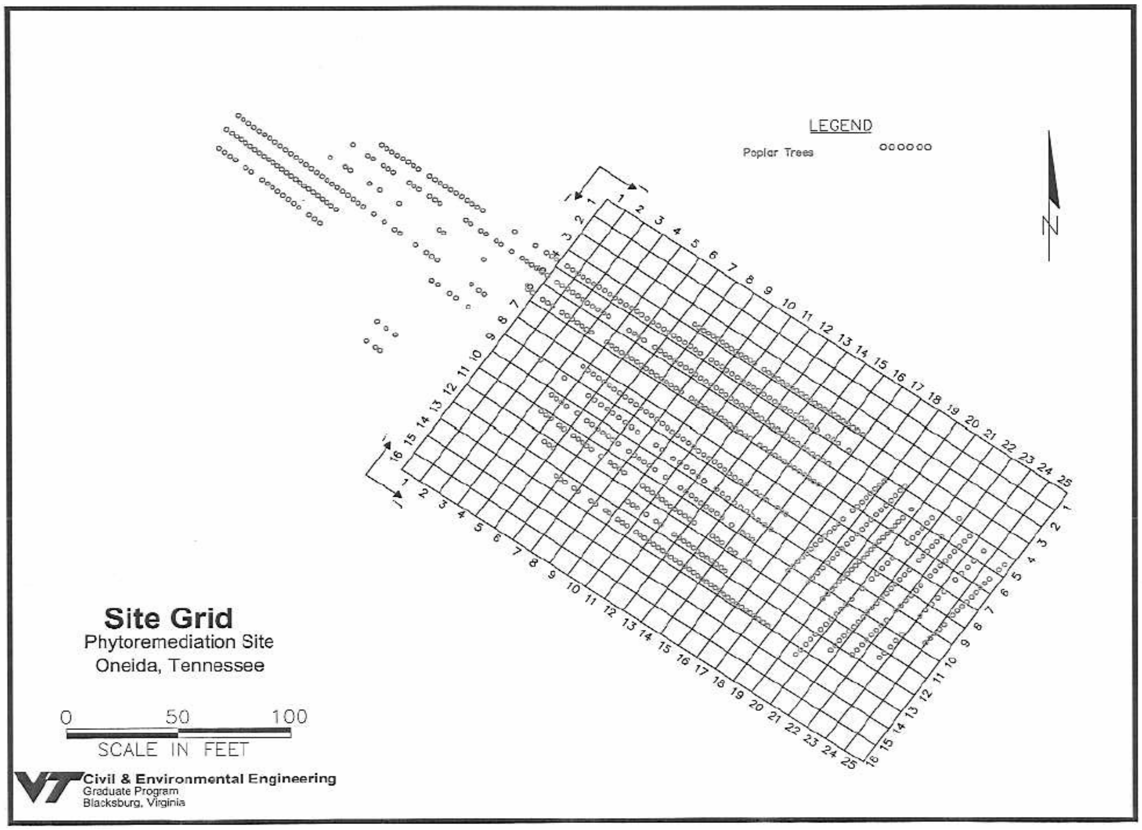


Figure 4.8 Division of phytoremediation system into 10 x 10 foot cells.

To establish representative areas, a block of cells was assigned to each of the points of observation: MW6, P4, and P25. Each block of cells contained the point of observation within its center cell. A center cell plus the eight cells immediately adjacent comprised a 900 square-foot area (3 cells x 3 cells) surrounding each observation point. Next, the representative areas were increased to 5-cell x 5-cell blocks equal to 2500 square feet. This was the maximum area which could be used without overlapping representative areas. Figures 4.9 and 4.10 illustrate both representative area sizes.

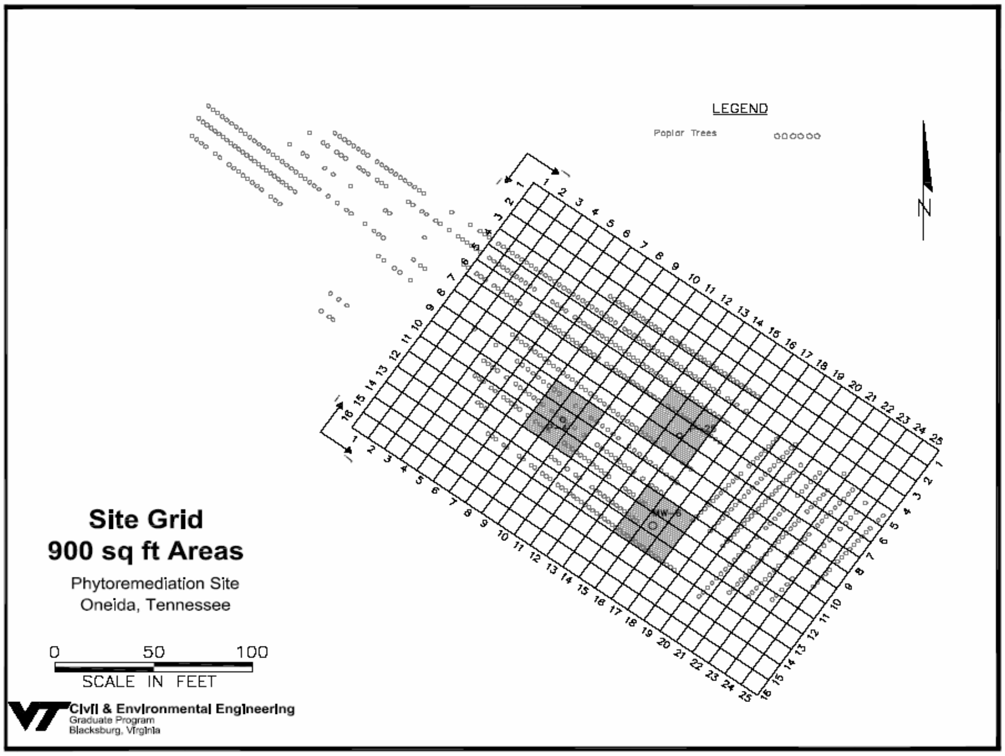


Figure 4.9 Representative 900 square-foot area around each observation point.

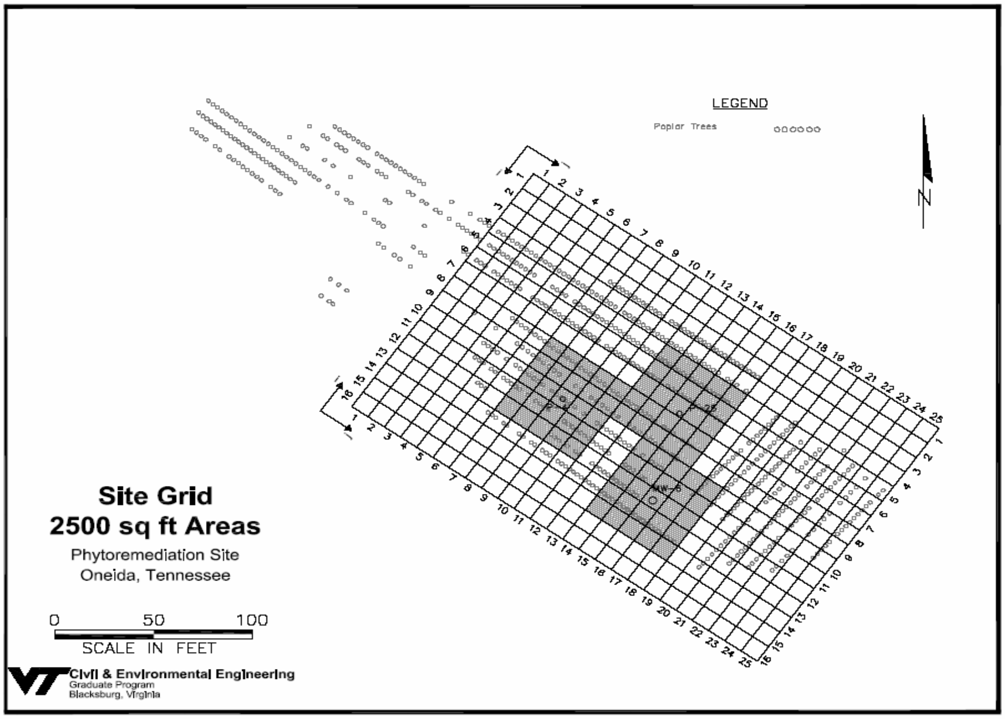


Figure 4.10 Representative 2500 square-foot area around each observation point.

If the volumetric rate of water leaving the representative areas can be attributed to direct transpiration, then that rate can be divided by the number of trees within the representative area to calculate the volumetric rate of direct transpiration in cubic feet per day per tree. However, since it was known that the size of the trees within each area varies and that the variability of transpiration rates between trees can be correlated to tree diameter, the volumetric direct transpiration rate for the area was distributed amongst the trees within that area based on tree diameter to yield per tree volumetric direct transpiration rates, $Q^{T}{}_{DT}$ (gal/day-tree).

The first step to distributing volumetric transpiration rates to trees located within a specific area was to determine the diameters of each tree found within that area. Calder (1993) showed that tree transpiration is directly correlated to the square of diameter at breast height (DBH). First the sum of the squares of the diameters within the area is calculated. Then, the square of the DBH of each individual tree is divided by the sum of the squares of all the tree diameters within the representative area to yield volumetric transpiration for the individual tree. An example using a 900 square-foot area around MW6 is shown:

$$T_{DT} = 0.01\frac{feet}{day} \qquad A = 900\, feet^{2}$$

$$Q_{DT(900)} = (T_{DT})x(A) = (0.01\frac{feet}{day})x(900\, feet^{2}) = 9.0\frac{feet^{3}}{day}$$

$$Q^{Ti}{}_{DT} = (Q_{DT(900)})x\left(\frac{\beta_i}{\sum_{1}^{N}\beta_i}\right)$$

where: $\beta_i = (\text{DBH}_i)^2$

DBH_i = diameter at breast height of any tree, *i*

N = number of trees within representative area

This calculation is performed for every tree within the representative area and tabulated. Table 4.3 illustrates this calculation and distribution.

Table 4.3 Sample calculation for estimating the volumetric transpiration rates of trees within a nine-cell (900 ft^2) area surrounding the observation point (MW6).

MW6-AVERAGE MONTHLY TRANSPIRATION VALUES DISTRIBUTED OVER SURROUNDING 900 SQ. FT AREA

MAY 6, 2004 TRANSPIRATION RATE RECORDED AT MW6 = 0.00999 ft/day

$Q_{DTi} = T_{DT}$ x A_{cell} = 0.00999 ft/day x 30' x 30' = **8.991** ft^3/day

$\beta_i = (DBH_i)^2$

$Q^T_{DTi} = Q_{DTi}$ x $\beta / \sum_{1}^{N} \beta_i$

Cell # i,j	Tree #	Circum (feet)	DBH (feet)	β (feet^2)	β/Σβ -	Q^T_{DTi} (ft^3/day-tree)	Q^T_{DTi} (gal/day-tree)
11,15	3T4	1.21	0.39	0.1483	0.057	0.512	3.832
	3T5	1.29	0.41	0.1686	0.065	0.582	4.356
11,16	3T1	1.21	0.39	0.1483	0.057	0.512	3.832
	3T2	1.42	0.45	0.2043	0.078	0.706	5.278
11,17	11T1	1.58	0.50	0.2529	0.097	0.874	6.534
12,15	2T1	1.29	0.41	0.1686	0.065	0.582	4.356
	2T2	0.94	0.30	0.0895	0.034	0.309	2.313
	2T3	0.75	0.24	0.0570	0.022	0.197	1.472
13,15	1T12	1	0.32	0.1013	0.039	0.350	2.617
	1T13	1	0.32	0.1013	0.039	0.350	2.617
	1T14	1.42	0.45	0.2043	0.078	0.706	5.278
	1T15	1.13	0.36	0.1294	0.050	0.447	3.342
13,16	1T8	0.75	0.24	0.0570	0.022	0.197	1.472
	1T9	0.75	0.24	0.0570	0.022	0.197	1.472
	1T10	1.42	0.45	0.2043	0.078	0.706	5.278
13,17	1T4	1.25	0.40	0.1583	0.061	0.547	4.090
	1T5	0.67	0.21	0.0455	0.017	0.157	1.175
	1T6	1.17	0.37	0.1387	0.053	0.479	3.583
	1T7	1.29	0.41	0.1686	0.065	0.582	4.356
			SUM	**2.603**	**1.000**	**8.991**	**67.253**

The first step of this calculation was to multiply the direct transpiration rate, T_{DT} (feet/day) recorded at MW6 on May 6, 2004 by the 900 square-foot representative area to yield a volumetric transpiration rate (Q_{DT}) of 8.991 ft^3/day. This value was then distributed to the trees within the 900 square-foot area based a weighting factor which is the square of the diameter at breast height (DBH). The volumetric direct transpiration rate per tree is found for each tree within the representative area by multiplying Q_{DT} by the fraction of the square of the tree diameter within the area ($\beta_i / \sum_{1}^{N} \beta_i$). The result is a per tree volumetric transpiration rate for each tree within that area. In the last step, units of cubic feet per day-tree were converted to gallons per day-tree.

The calculation shown in Table 4.3 was made for each direct transpiration rate determined by the Groundwater Recession Comparison method and by White's Equation for each observation point over both a 900 and 2500 square foot area. Plotting Q^{T}_{DT} versus DBH yields a power equation $y = kx^2$ where k is the per tree volumetric direct transpiration coefficient. An example is illustrated in Figure 4.11. Two k-values were determined for each calculated transpiration (T_{DT}) rate: one for the 900 square-foot area and one for the 2500 square foot area. These k-values were then used to form relationships with other parameters such as time of year and saturated thickness. Ultimately, k-values from each of the 3 observation locations (P4, P25, and MW6) were applied to all of the trees on site so that a range of per tree volumetric direct transpiration rates could be established for the entire phytoremediation system.

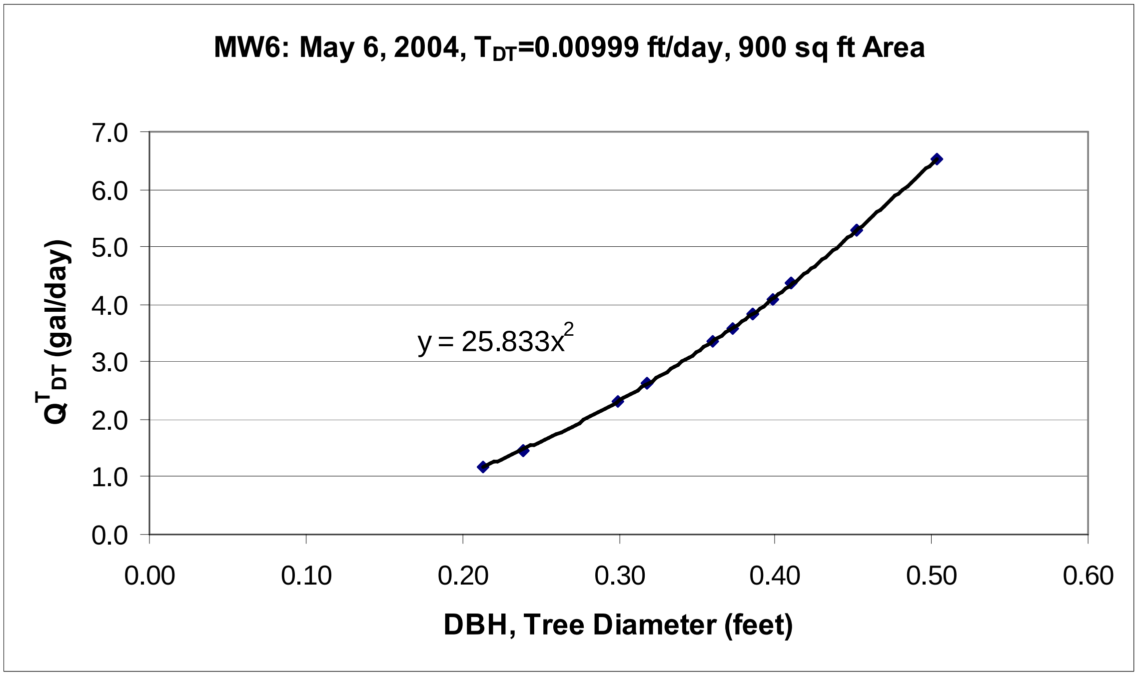


Figure 4.11 Range of per tree direct transpiration rates around MW6 for May 6, 2004 duration.

4.5 Determination of the Direct Uptake of Naphthalene

The final objective of this research is to determine the amount of naphthalene mass leaving the system via direct uptake. This is accomplished by overlaying the transpiration site grid with the naphthalene concentration data and then multiplying volumetric transpiration rates by chemical concentration data and the Transpiration Stream Coefficient Factor (TSCF) in each cell. The sum of all the cells yields a mass loss rate of naphthalene in mg/day leaving the system.

4.5.1 Naphthalene Concentration Data

Chemical concentration data has been monitored at the Oneida phytoremediation site since the project's inception (Widdowson et al, 2005). Groundwater samples were taken from the multilevel samplers which are located in the contaminant zone illustrated in Figure 4.12. Concentrations were measured twice a year from the multilevel samplers and recorded in a spreadsheet. As previously mentioned, for every multilevel sampler, there are up to eight ports from which to sample, each representing a different depth within the subsurface (ranging from approximately 3 to 11 feet below land surface). As observed by continuous water level records, the saturated thickness of the aquifer varies

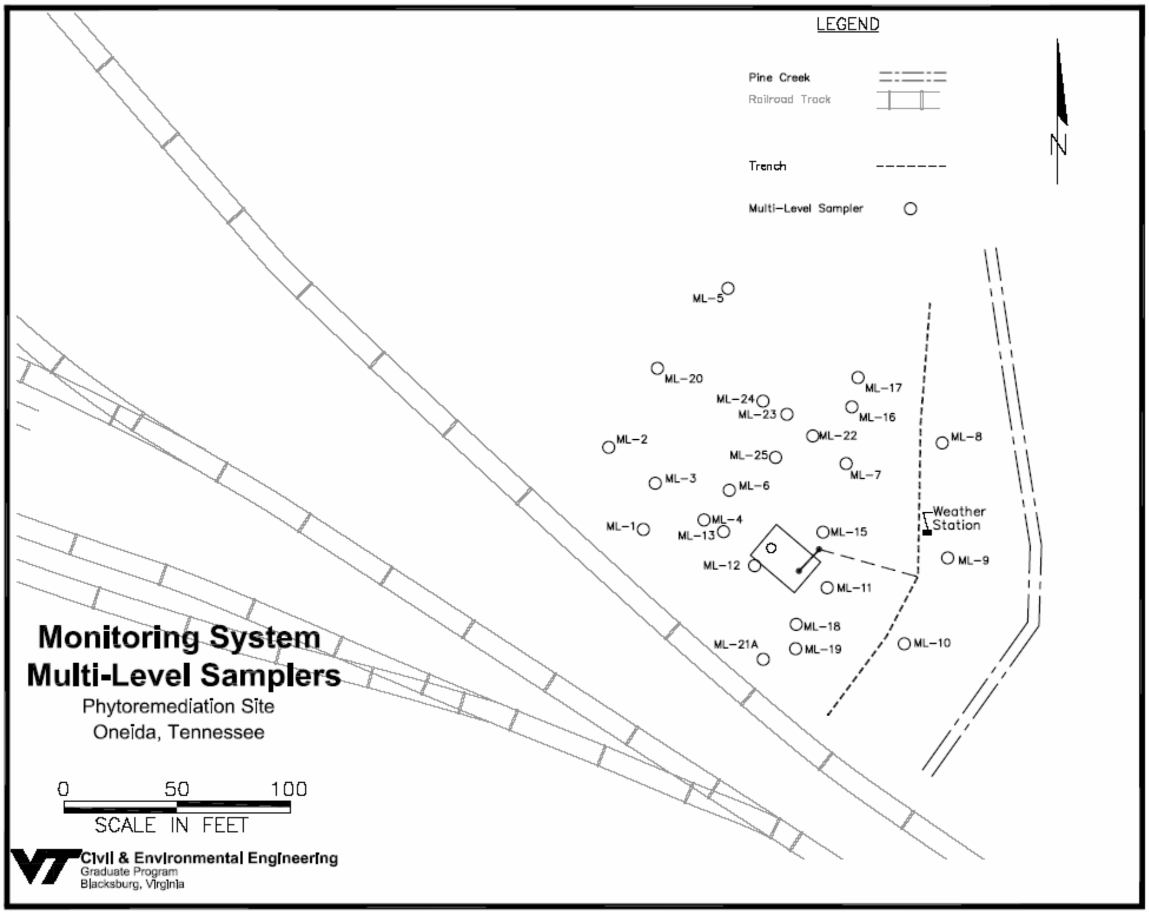


Figure 4.12 Location of multilevel samplers at the Oneida phytoremediation site.

from 1 to 8 feet over time. This affects the number of groundwater samples taken from each multilevel sampler since pumping from each port is dependent on the height of the water table. For instance, during the late winter when the saturated zone was relatively thick, all eight ports were sampled at each multilevel sampler. However, during mid-summer when the water table was relatively low, many of the ports were not sampled due to lack of available water at that height within the sampler. All data recorded between 1997 and 2004 was logged in a spreadsheet.

4.5.2 Spatial Distribution of Naphthalene

For the purpose of this study, the concentrations utilized for analysis were taken from the upper portion of the saturated thickness based on the assumption that the roots of the poplar trees utilize the uppermost water found in the capillary fringe and upper limits of the saturated zone. For the purpose of comparison, one data set consists of naphthalene data taken from the uppermost port in each sampler while the other is comprised of the average concentration between the upper two ports of each sampler. The naphthalene concentrations were input into Groundwater Modeling System (GMS) and overlaid with the grid used for the direct transpiration calculation (Figure 4.13).

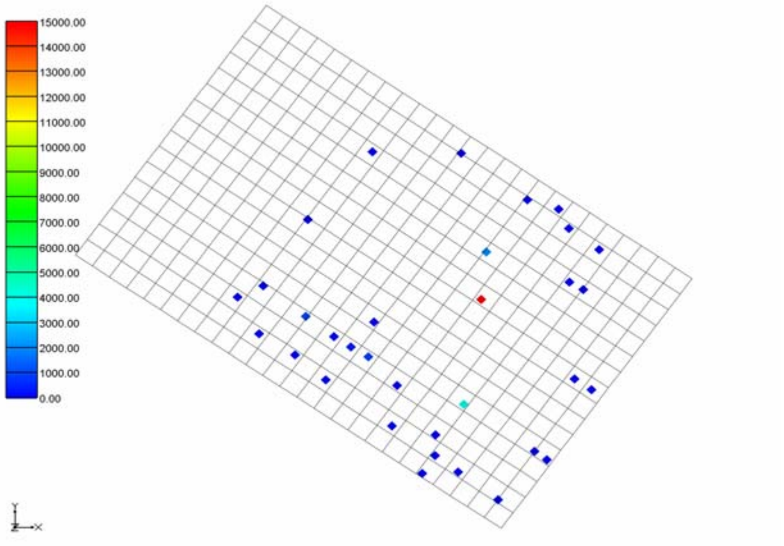


Figure 4.13 Average naphthalene concentrations derived from the upper two ports of multilevel samplers at the Oneida phytoremediation site in June 1999.

Using a linear interpolation scheme within GMS, groundwater concentration contours were generated for each of the naphthalene data sets. To better identity the lowest naphthalene concentration, additional points were added around the periphery of the plume boundary. The output from GMS provides the interpolated naphthalene concentration for each cell. An example of this interpolation scheme is illustrated in Figure 4.14.

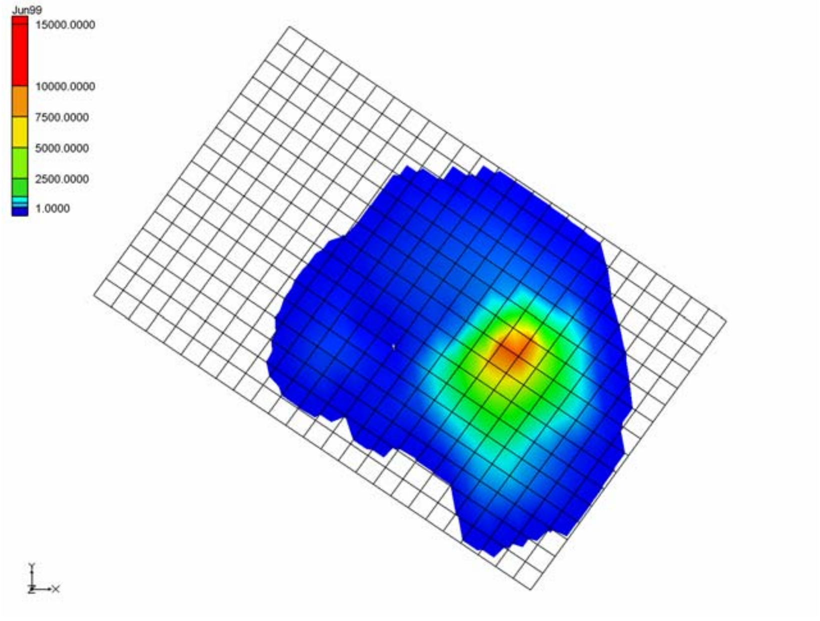


Figure 4.14 Oneida phytoremediation system naphthalene concentration contours interpolated from point measurements taken in June 1999.

4.5.3 Calculation of Mass Removal of Naphthalene via Plant Uptake

Using the concentration of naphthalene of each cell, the equation to calculate plant uptake is:

$$U_{cell} = (TSCF)\,(T_{cell})\,(C_{cell}) \qquad (5.1)$$

where: U_{cell} = rate of contaminant uptake in a given cell (mg/day),

TSCF = Transpiration Stream Concentration Factor (unitless),

T_{cell} = sum of volumetric direct transpiration of trees within cell (L/day),

C_{cell} = soil water concentration of naphthalene (mg/L).

The TSCF is calculated using the following equation developed by Burken and Schnoor (1998):

$$TSCF = 0.784 \times EXP\left(\frac{-\left(\log Kow_{(Napthalene)} \; -1.78\right)^2}{2.44} \right) = 0.304$$

The overall rate of removal for the site is the sum of all U_{cell} values. The value for T_{cell} is the direct transpiration rates estimated for the particular day concentration data was measured.

4.5.4 Plot of Discrete Water Level Measurements

Discrete water level measurements performed on a monthly basis were used to create groundwater contours and water table profiles. To-scale mapping of the water table at the Oneida site is useful for observing water table elevation trends across this site.

4.5.5 Groundwater Contours

Groundwater contours were created by digitizing recorded water table elevations using AutoCAD Land Development™ software which linearly interpolated between point elevations (discrete water level measurements). These contours were used to establish hydraulic gradient and direction of flow. In addition, by analyzing the groundwater contours over time (on a monthly basis), the existence of cone of depression created by the transpiring trees could be determined. An example of groundwater contours for the Oneida phytoremediation site for March 6, 2004 is illustrated in Figure 4.15.

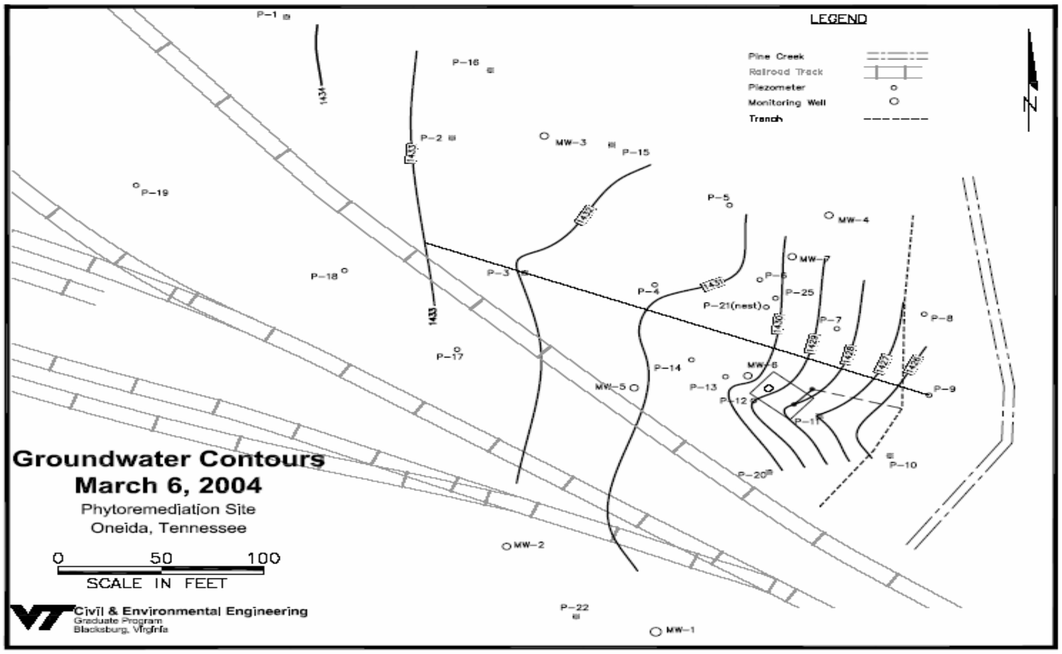


Figure 4.15 Groundwater contours interpolated from discrete water level measurements taken on March 6, 2004.

4.5.6 Water Table Profiles

In addition to plan views of the water table, profiles of the water table were created using the groundwater contours. The purpose of these profiles is to examine the gradient of the water table with regard to the location of the trees and the time of season. For instance, if the gradient is steeper in an area beneath the trees, it can be partly assumed this is a result of the sink created by the transpiring trees. These profiles are also useful for the observation of the time trend of water table decline in the aquifer. For example, it is expected that the depth to water across the site is much higher during March than in July. An example of the water table profile between P3 and P9 is illustrated in Figure 4.16.

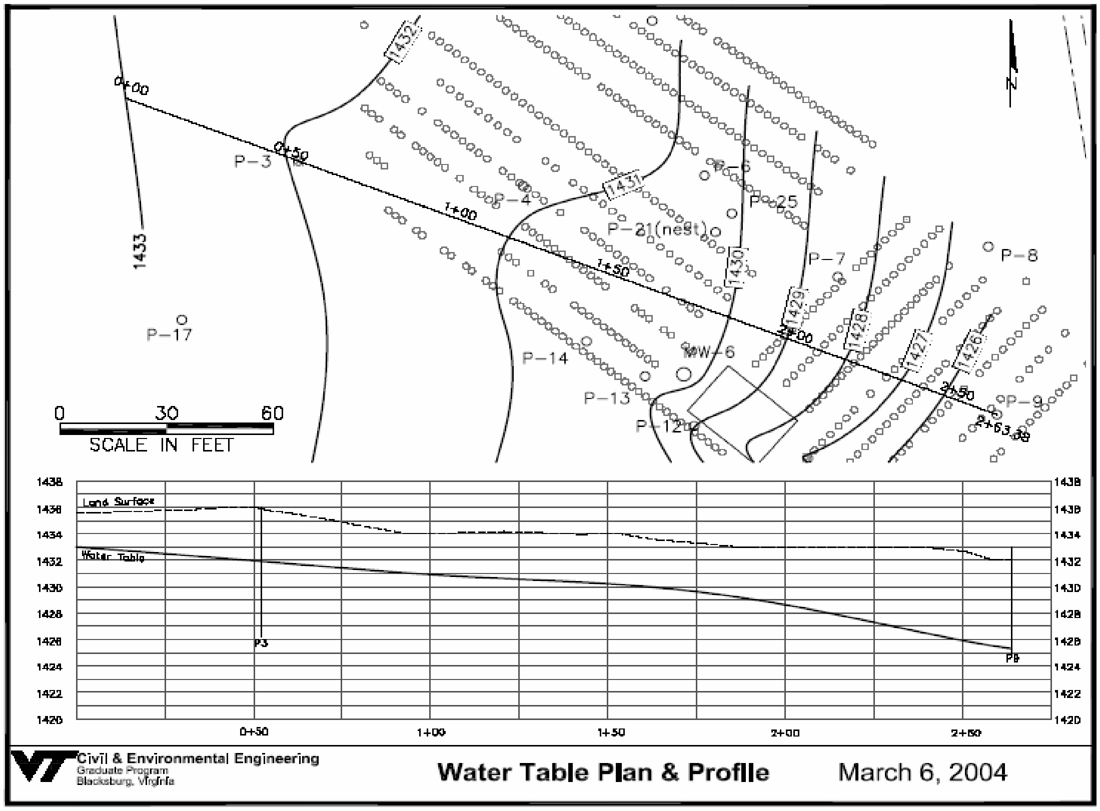


Figure 4.16 Water table profile and groundwater contours for March 6, 2004. The profile line with station labels 0+00 to 2+63 intersects P3 and P9.

Ultimately, the plan and profile of a series of groundwater contours collected between March and October was used to develop conclusions about the impact of the phytoremediation system on the saturated thickness of the shallow aquifer underlying the Oneida site.

5 RESULTS AND DISCUSSION

5.1 Summary of Data Utilized for this Study

During the course of this analysis, a variety of data sources were used to complete the objectives of this project. To gain understanding about transpiration rates and plant uptake of naphthalene at the Oneida phytoremediation site, continuous water level data collected in 2004 were analyzed and compared with data previously collected by others between 1998 and 2003. Weather data were recorded from March through October 2004 using an on-site weather station. Additional rainfall data were compiled from records by the National Climatic Data Center (NCDC). Intermittent on-site weather data recorded between 2000 and 2003 were collected by others. Between 1997 and 2004, naphthalene concentration data from groundwater were collected bi-annually from multilevel samplers. Discrete water level measurements were performed on a monthly basis for this study between March 2004 and October 2004. Discrete water level measurements taken by others were available for 1998 through 2001.

5.1.1 Oneida Rainfall Data

Rainfall amounts were collected intermittently on-site between 2000 and 2004. In order to have continuous monthly and yearly rainfall amounts at Oneida, site weather station data were subsidized with local rainfall data collected at the Oneida wastewater treatment plant (WWTP). Besides the on-site weather station, the wastewater treatment plant rain gauge is the closest recorded rain gauge to the phytoremediation site. All rain data logged at the Oneida WWTP are recorded into the National Climatic Data Center database and are available for public use online at: http://www.ncdc.noaa.gov/oa/ncdc.html.

To make assumptions about the impacts of rainfall on groundwater levels at the Oneida site, yearly rainfall records were compared to long-time averages. This was important because drought years can have significant impacts on tree performance and wet years can potentially influence the mobility of the contaminant plume. A summary of monthly rainfall from 1999-2004 is shown in Table 5.1 and a comparison of yearly totals (1999-2004) versus 100-year average yearly totals is illustrated in Figure 5.1.

Table 5.1 Precipitation record for Oneida, Tennessee. Rain gauge located at Oneida wastewater treatment plant (WWTP). Data Source: National Climatic Data Center.

Observed Month	Precipitation Record for Oneida, Tennessee						
	2004 (inches)	2003 (inches)	2002 (inches)	2001 (inches)	2000 (inches)	1999 (inches)	100-Year Average*
J	1.82	1.83	7.26	4.09	4.14	8.03	4.7
F	4.28	9.37	2.31	5.88	4.19	4.37	4.2
M	2.82	1.46	10.23	3.94	3.24	3.85	5.5
A	4.28	9.58	3.06	2.49	6.32	4.38	4.2
M	5.89	6.28	4.68	3.46	4.54	4.29	5.5
J	3.00	8.70	4.64	3.88	6.21	7.13	4.8
J	5.00	4.19	3.47	5.99	2.39	4.53	5.0
A	5.50	4.72	2.39	2.47	2.45	2.67	4.5
S	7.52	8.89	5.73	3.77	1.74	0.6	3.7
O	3.78	2.27	3.18	3.07	0.57	2.47	3.7
N	5.74	4.77	4.10	2.88	2.53	2.62	4.5
D	4.80	3.62	6.82	4.53	2.75	2.31	4.8
Year Total	**54.43**	**65.68**	**57.87**	**46.45**	**41.07**	**47.25**	**55.1**

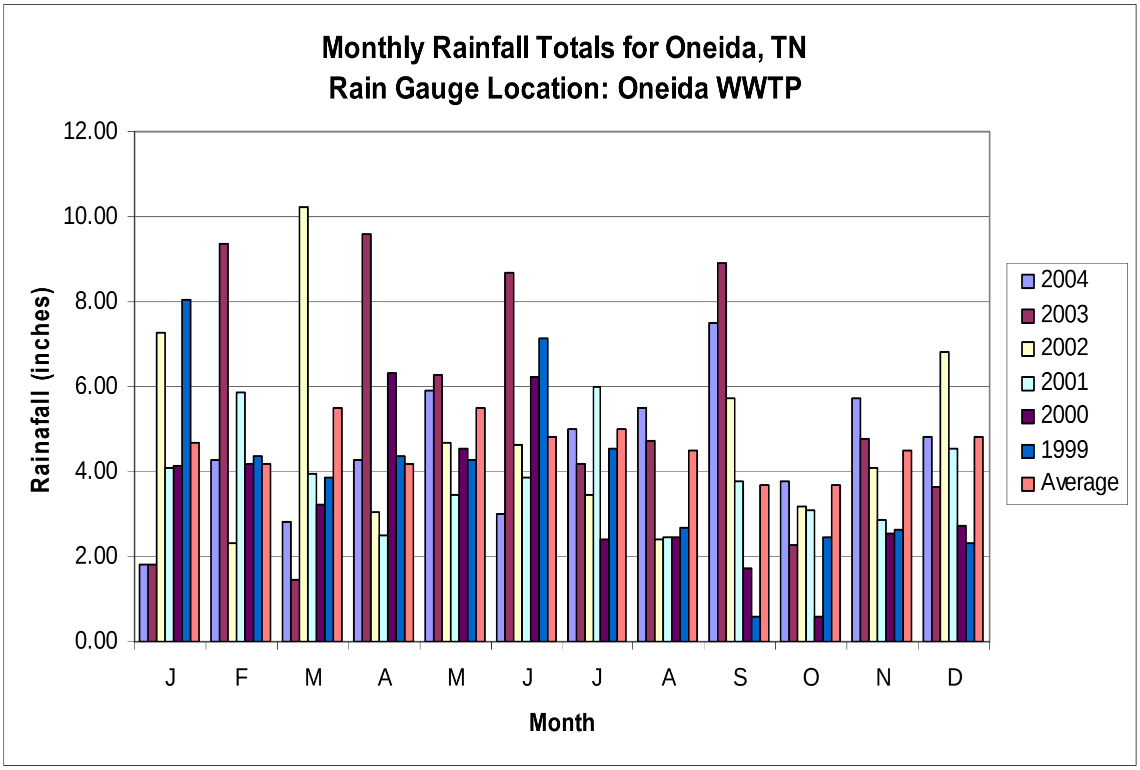


Figure 5.1 Comparison of monthly rainfall totals from 1999 to 2004 and 100-year average.

Rainfall, the source of recharge, is a significant parameter with regard to groundwater levels and direct transpiration. Due to its consistency, rainfall data recorded from 1999-2004 at the Oneida WWTP were used to determine yearly and monthly trends. In general, yearly rainfall values were used to determine if a particular year was above or below average. Table 5.1 shows that during 2004, Oneida received an average amount of rainfall, 2003 was a relatively ‘wet’ year, 2002 was about average, and 2001, 2000, and 1999 were probably considered drought years. For a phytoremediation system, however, it is equally important to observe monthly rainfall trends. Monthly rainfall averages are important since a phytoremediation system only impacts groundwater levels between March and October. For instance, though 2004 as a whole appeared average, June was relatively dry compared to the average (3.0 versus 4.8 inches). September 2004 was significantly above average with 7.58 inches versus the average 3.70 inches. Though not considered a drought year by yearly averages, 2002 received below average rainfall from April through October; months when the phytoremediation system was considered to be active.

During 2004, the weather station at the Oneida phytoremediation site operated continuously from March 6th to October 8th and recorded on a half-hour interval. This relatively short interval indicated precise occurrences of rainfall on-site. For the purpose of determining direct transpiration rates, it was important to know exactly when rainfall occurred at the Oneida phytoremediation site because the Groundwater Recession Comparison method and White’s Equation must be performed during periods which were not immediately influenced by rainfall. Figure 5.3 illustrates the rainfall record from the weather station for 2004.

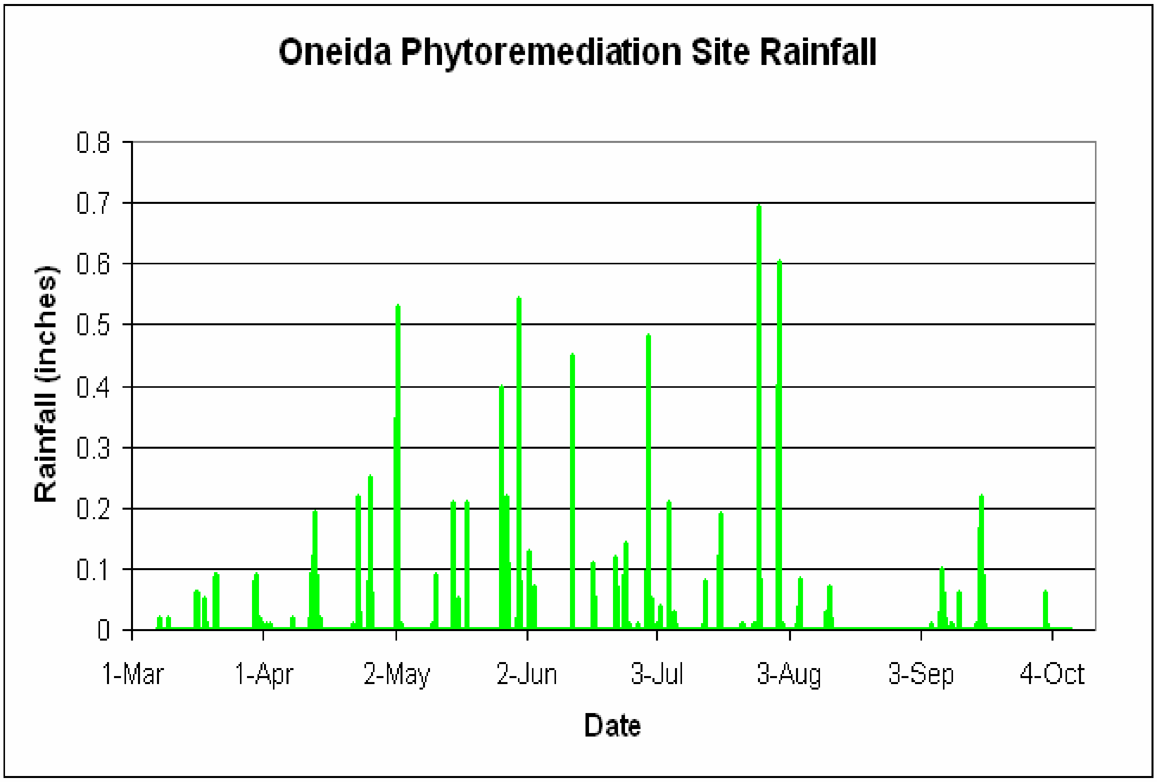


Figure 5.2 Rainfall recorded by weather station at phytoremediation site, 2004.

The values reported from the phytoremediation site weather station during August 2004 were skewed by a weather station malfunction which occurred between August 20th and September 3rd. During that time, the Oneida WWTP indicated that it rained a total of 2.26 inches.

5.1.2 Continuously Recorded Water Table Elevations

The type of groundwater data primarily used for the quantification of direct transpiration rates were water level data which were continuously recorded from observation points MW6, P4, and P25. For the 2004 season, three Global Level Loggers were utilized to collect water level data from piezometers MW6, P4, and P25. These observation points were chosen for two reasons: 1) All were close to or within the contaminant plume area and 2) previous data existed from these locations which were used for comparison. The transducers were set on March 6, 2004. In April 2004 a fourth Global Level Logger was placed in P3. A summary of water level data (with rainfall data) from MW6, P4, P25, and P3 is illustrated in Figures 5.3-5.4.

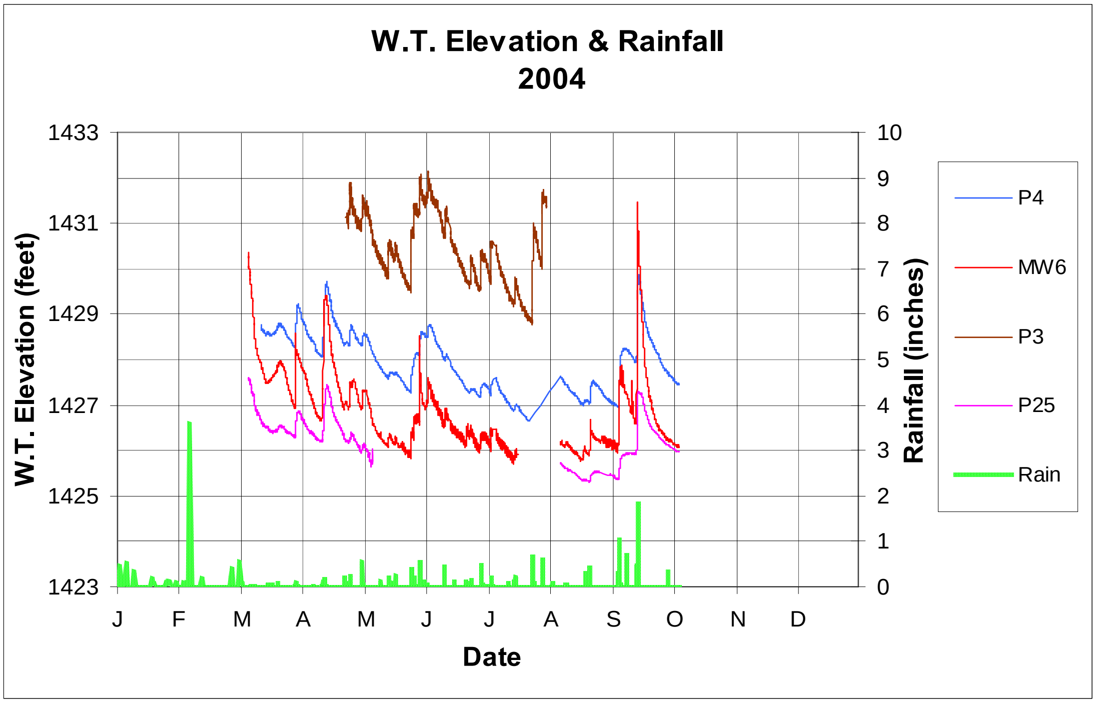


Figure 5.3 Continuous water table elevation and rainfall data from 2004.

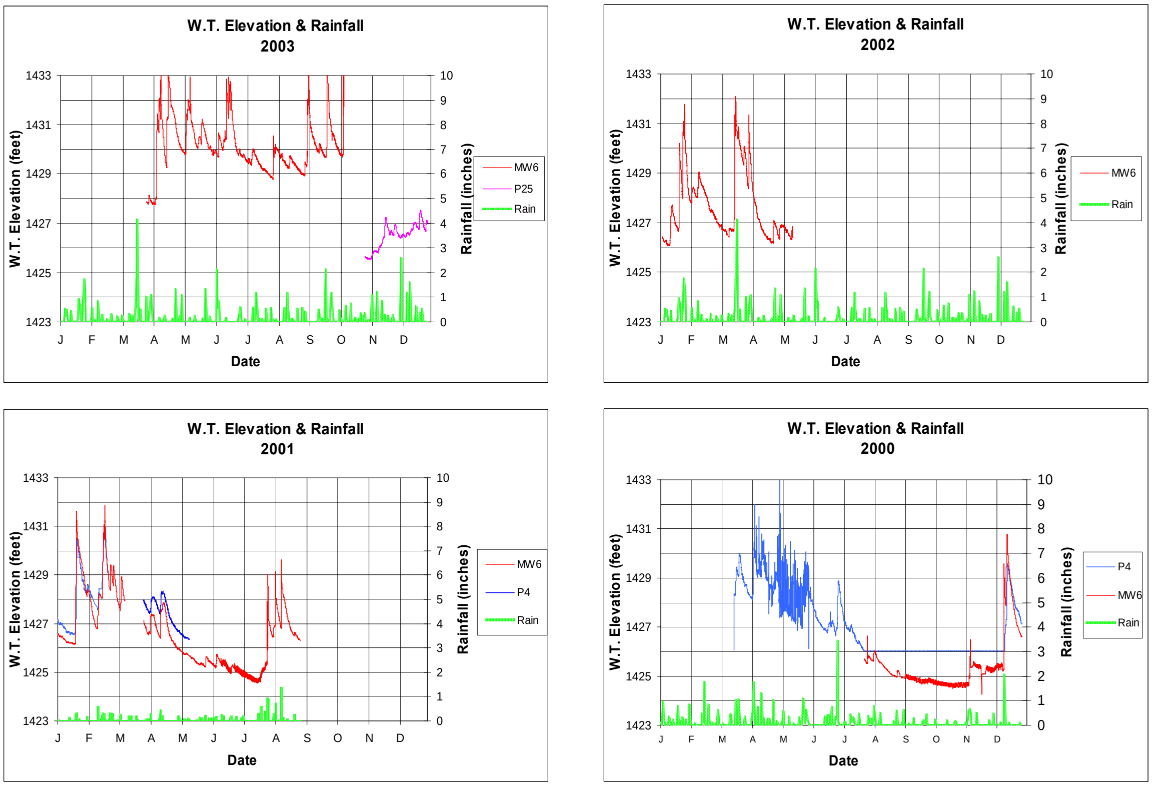


Figure 5.4Continuous water table elevation and rainfall data, 2000-2003.

It is evident from Figures 5.3 – 5.4 that precipitation influences water levels at the Oneida phytoremediation site. During times of significant rainfall (long durations of light rainfall, short durations of intense rainfall, or both), the elevation of the water table at the three observation points increased, sometimes dramatically. The magnitude of fluctuations tends to change over the course of one year depending on the season. During the first part of the year (winter and early spring), precipitation caused the water levels in the piezometers to increase dramatically. Depending on the nature of the rain event, this tendency was subject to variance. During the late spring through mid to late summer, rainfall of similar quantities tended to cause fluctuations of the water table of a magnitude which was smaller than that seen during the first part of the year. A return to greater fluctuations occurred at the beginning of the fall season and continues through winter. This trend can be observed during 2004, 2002, 2001, and 2000. This trend is observed to a lesser degree during 2003 due to large amounts of consistent rainfall which fell during that year. In addition, P3 data illustrated in Figure 5.3 exhibited greater fluctuations in water levels resulting from rain events during the late spring and summer than MW6, P4, and P25. It should be noted that P3 is not found within the dense area of trees, but rather in an open area with less than 10 poplar trees within a 50-foot radius. This suggests that transpiring trees influence the recession of the water table.

The relationship between rainfall and water levels was most apparent at MW6 due to consistent data which were collected there between 2001 and 2004. With regard to rainfall, 2004 was relatively average while 2001 was considered a drought year. This difference is evident when comparing water table elevations observed at MW6 during 2004 and 2001 (Figures 5.5). For simplicity, a 15-day running average for MW6 data was employed in order to better illustrate groundwater trends. As a result of average rainfall during summer 2004, the water table elevation at MW6 remained consistently near1426 feet. As a result of below average rainfall during summer 2001, the water table elevation at MW6 remained below 1426 feet for a relatively long duration. The elevation dipped below 1425 feet in July 2001.

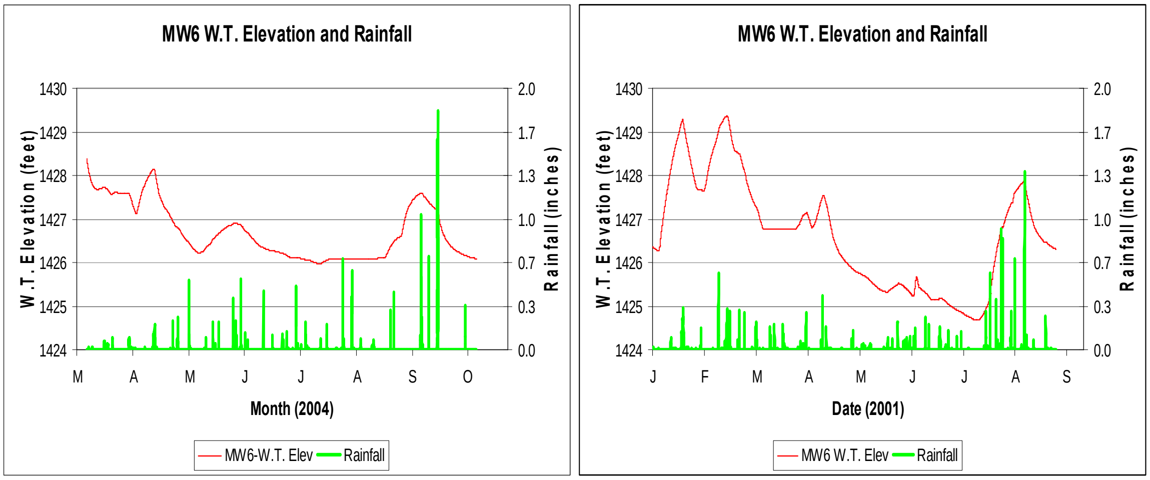


Figure 5.5 Running average of continuous water table elevation and daily rainfall data from 2004 and 2001.

5.1.3 Discrete Water Level Data

The overall trend of groundwater levels indicated a noticeable decrease between spring and summer. Measurements were performed once a month through October and are shown in Table 5.2. The first round of discrete water level measurements occurred on March 6, 2004.

Water levels decreased relatively significantly between March 6, 2004 and April 24, 2004. During the period, the trees on-site became leafed and began the seasonal transpiration process. From April 24th through October 8th while the trees were leafed, groundwater levels at the Oneida phytoremediation remained relatively low. With respect to the recording location, no water level recorded between April and October (active season) exceeded the water levels recorded during March (dormant season). In addition, water table elevations in some piezometers were not detected because the elevation of the water table was below the bottom of casing of the piezometer (indicated by "dry" in Table 5.2). This was evident in P4, P8, P20, P21A, P21B, and P21C in August and early September.

Rainfall amounts recorded between March and October 2004 (Table 5.1 and Figure 5.2) indicate that March received the least rainfall of all the months during which discrete water level measurements were performed in 2004. This indicates between March 6th and April 24th an additional sink for groundwater was created by the hybrid poplars and continued into early October.

Table 5.2 Discrete water level measurement results for 2004.

Top of Casing(TOC) Elevations valid 1996-July 2004													TOC Elevations valid August 2004-Present						
Well ID	TOC (feet)	Well Depth (ft BTC)	3/6/04 WL (ft BTC)	W.T. Elev (feet)	4/24/04 WL (ft BTC)	W.T. Elev (feet)	5/24/04 WL (ft BTC)	W.T. Elev (feet)	6/15/04 WL (ft BTC)	W.T. Elev (feet)	7/6/04 WL (ft BTC)	W.T. Elev (feet)	TOC (feet)	8/9/04 WL (ft BTC)	W.T. Elev (feet)	9/3/04 WL (ft BTC)	W.T. Elev (feet)	10/8/04 WL (ft BTC)	W.T. Elev (feet)
P1	1436.79	6.79	2.48	1434.31	3.29	1433.50	4.3	1432.49	3.56	1433.23	3.78	1433.01	1436.79	3.80	1432.99	4.50	1432.29	4.43	1432.36
P2	1436.96	9.94	4.39	1432.57	5.40	1431.56	6.61	1430.35	5.66	1431.30	4.88	1432.08	1436.96	5.62	1431.34	6.95	1430.01	6.66	1430.30
P3	1435.98	9.87	4.04	1431.94	5.10	1430.88	6.31	1429.67	5.28	1430.70	4.29	1431.69	1435.98	5.67	1430.31	6.65	1429.33	6.42	1429.56
P4	1435.04	9.74	4.95	1430.09	6.49	1428.55	7.74	1427.30	7.02	1428.02	7.49	1427.55	1435.04	7.48	1427.56	dry	dry	7.67	1427.37
P5	1434.65	9.63	3.22	1431.43	6.66	1427.99	7.92	1426.73	7.16	1427.49	7.3	1427.35	1434.65	7.64	1427.01	8.26	1426.39	7.86	1426.79
P6	1434.17	9.43	-	-	7.32	1426.85	-	-	8.06	1426.11	8.37	1425.80	1434.17	8.34	1425.83	8.65	1425.52	8.17	1426.00
P7	1432.77	9.77	-	-	6.45	1426.32	7.17	1425.60	7.11	1425.66	7.44	1425.33	1432.77	7.33	1425.44	7.51	1425.26	7.00	1425.77
P8	1432.14	NM	5.67	1426.47	dry	Dry	dry	dry	dry	dry	dry	Dry	1432.14	dry	dry	dry	dry	dry	dry
P9	1433.01	8.09	7.71	1425.30	7.96	1425.05	8.02	1424.99	7.98	1425.03	8	1425.01	1433.01	8.00	1425.01	7.96	1425.05	7.95	1425.06
P10	1432.19	10.23	6.99	1425.20	7.11	1425.08	7.23	1424.96	7.15	1425.04	7.17	1425.02	1432.19	7.19	1425.00	7.13	1425.06	7.12	1425.07
P11	1432.74	10.00	5.83	1426.91	7.19	1425.55	7.61	1425.13	7.43	1425.31	7.45	1425.29	1432.74	7.52	1425.22	7.53	1425.21	7.45	1425.29
P12	1433.26	9.31	4.24	1429.02	6.39	1426.87	7.31	1425.95	7.31	1425.95	7.11	1426.15	1433.26	7.54	1425.72	7.72	1425.54	7.56	1425.70
P13	1434.68	9.97	3.12	1431.56	6.25	1428.43	7.71	1426.97	-	-	-	-	1433.75	7.49	1426.26	7.76	1425.99	7.44	1426.31
P14	1433.98	8.23	3.41	1430.57	5.75	1428.23	7.35	1426.63	6.68	1427.30	7.01	1426.97	1433.98	7.28	1426.70	7.61	1426.37	7.13	1426.85
P15	1434.63	8.72	2.35	1432.28	3.10	1431.53	4.67	1429.96	3.25	1431.38	4.22	1430.41	1434.63	4.63	1430.00	5.51	1429.12	3.96	1430.67
P16	1436.04	9.09	3.78	1432.26	4.89	1431.15	6.63	1429.41	-	-	-	-	1435.85	5.28	1430.57	6.50	1429.35	6.14	1429.71
P17	1437.20	8.71	4.4	1432.80	4.66	1432.54	5.04	1432.16	4.75	1432.45	4.73	1432.47	1437.20	4.89	1432.31	5.15	1432.05	5.27	1431.93
P18	1437.17	8.46	-	-	-	-	-	-	-	-	-	-	1437.17	-	-	-	-	-	-
P19	1435.03	2.50	-	-	-	-	-	-	-	-	-	-	1435.03	-	-	-	-	-	-
P20	1434.80	8.32	4.23	1430.57	8.00	1426.80	dry	dry	dry	dry	dry	Dry	1434.80	dry	dry	dry	dry	dry	dry
P21A	1434.37	5.64	7	1427.37	dry	Dry	dry	dry	dry	dry	dry	Dry	1434.37	dry	dry	dry	dry	dry	dry
P21B	1434.36	6.21	dry	dry	dry	Dry	dry	dry	dry	dry	dry	Dry	1434.36	dry	dry	dry	dry	dry	dry
P21C	1434.37	8.36	6.87	1427.50	7.80	1426.57	8.5	1425.87	7.49	1426.88	7.5	1426.87	1434.37	dry	dry	7.45	1426.92	7.40	1426.97
P21D	1434.36	9.13	6.93	1427.43	7.83	1426.53	8.31	1426.05	8.36	1426.00	8.22	1426.14	1434.36	8.72	1425.64	8.13	1426.23	8.20	1426.16
P22	1433.90	9.12	2.7	1431.20	6.31	1427.59	7.4	1426.50	7.73	1426.17	5.42	1428.48	1433.90	7.31	1426.59	7.45	1426.45	7.85	1426.05
P25	1436.07		-	-	-	-	-	-	-	-	-		1433.57	7.85	1425.72	8.13	1425.44	7.63	1425.94
MW1	1433.64	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	1433.64	NM	NM	NM	NM	NM	NM
MW2	1436.10	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	1436.10	NM	NM	NM	NM	NM	NM
MW3	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	1437.28	7.00	1430.28	8.01	1429.27	7.75	1429.53
MW6	1434.81	NM	4.46	1430.35	7.74	1427.07	8.88	1425.93	8.32	1426.49	7.98	1426.83	1434.81	8.65	1426.16	8.82	1425.99	8.70	1426.11

5.1.4 Tree Growth

As of the last count in June 2004, the Oneida phytoremediation system had 693 live hybrid poplar trees whose diameters ranged from 0.5 to 7.5 inches. Based on tree circumference, surviving trees grew approximately 16% between June 1998 and June 1999, 46 % between June 1999 and January 2001, and approximately 44% between June 2001 and June 2004. Between June 1998 and June 2004, the amount of live trees on-site diminished from 1,036 to 693. Figure 5.6 illustrates overall tree growth and the decrease in the number of trees between 1998 and 2004.

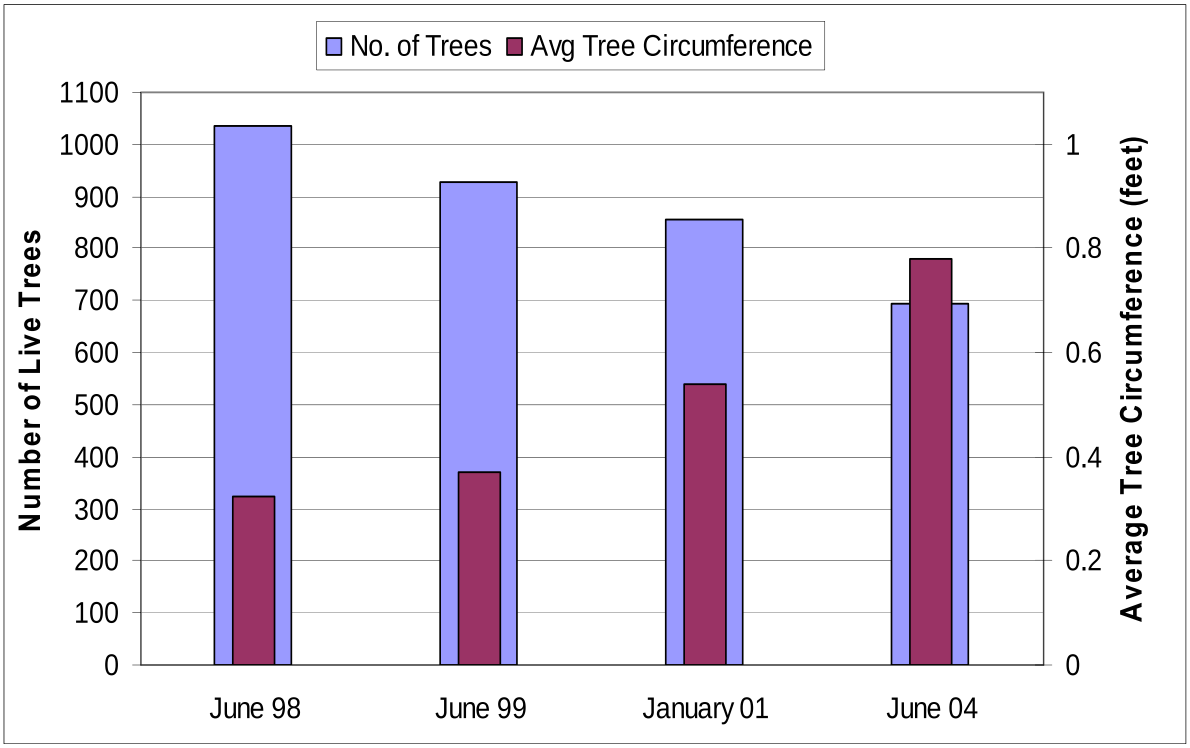


Figure 5.6 Hybrid poplar growth and survival at Oneida site between 1999 and 2004.

With respect to tree diameter, the distribution of hybrid poplar trees on-site is illustrated by Figure 5.7. Approximately 38% of the trees are between 0.20 and 0.29 feet followed by 31.3 % between 0.10 and 0.19 feet. 6.35 % of the trees are between 0.40 and 0.49 feet in diameter and 3% of the trees on-site are below 0.10 feet in diameter. 1.87% of the trees on-site are between 0.5 and 0.64 feet in diameter.

The average diameter within the 9-year old hybrid poplar stand at Oneida in June 2004 was 0.25 feet. At a 13-year old hybrid poplar stand in Flanders, Belgium, the average diameter was 1.37 feet (Meiresonne et al, 1999). Though there is an age difference, even if the size of the trees at Oneida increased 50% each year, the average diameter would still be less than observed in Belgium. This relatively significant difference indicates the trees at Oneida have not grown to their potential. The most apparent indicator of this is the existence of trees on-site which are greater than 0.6 feet in diameter. If some trees at the Oneida site were capable of growing to this size, then it is logical that all of the trees could have grown to this size under the right circumstances. The most noticeable difference between the two poplar stands (Oneida, TN and Flanders, Belgium) is tree spacing. At Oneida, the trees are spaced 3 feet apart within rows which are 10 feet apart. In Belgium, the trees were spaced 21 feet apart within rows which were approximately 25 feet apart (Meiresonne et al, 1999). If variability of transpiration rates between trees can be correlated to tree diameter, then tree spacing is a crucial component to maximizing the volume of water directly transpired from the saturated zone (Vose et al, 2003).

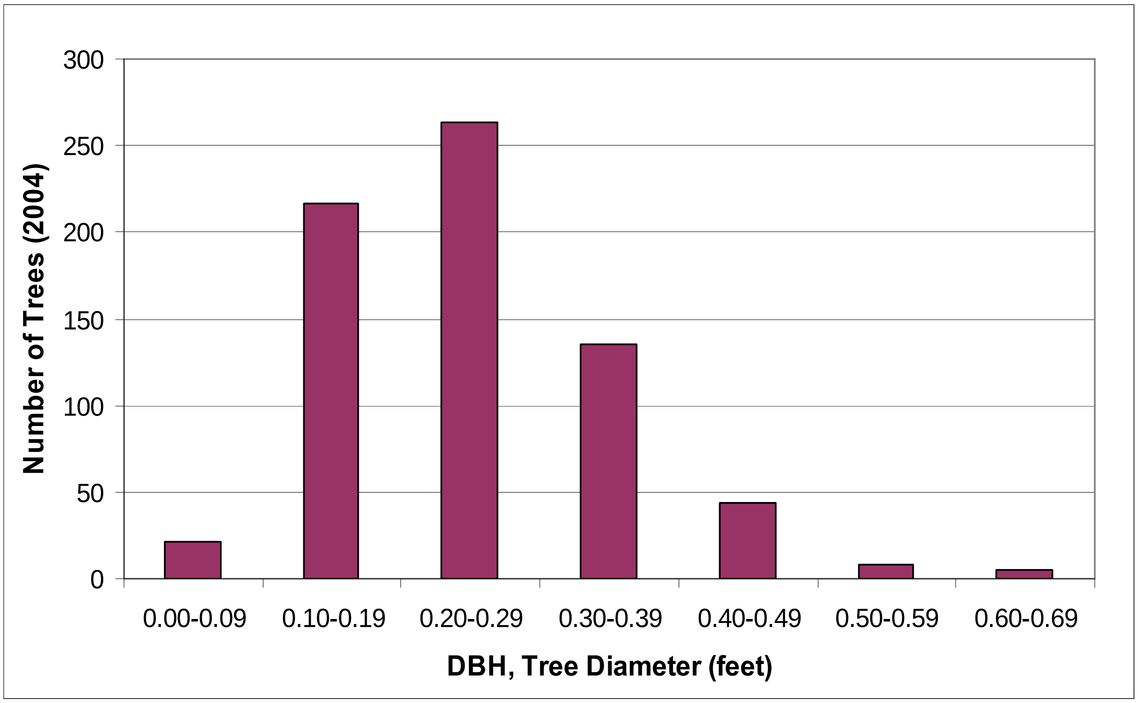


Figure 5.7 Range of tree diameters found at Oneida site (Total = 693), June 2004.

5.2 Quantification of Direct Transpiration Rates

5.2.1 Results of Groundwater Recession Comparison Method

To quantify direct transpiration T_{DT} (feet/day) using the Groundwater Recession Comparison (GRC) method, two groundwater recessions of similar time lengths and starting elevations from the same observation point are necessary. One groundwater recession duration must be from the dormant season when the trees are not active and the other from the active season when the trees are leafed. For the purpose of this study, active durations were chosen from the 2004 season only while dormant durations were chosen from both 2004 and previous years. The dormant season was considered to be from mid-October to mid-March and the active season from mid-to-late March to mid-October. This is approximately equivalent to the average 150-day growing season for the Oneida area. This determination of the dormant and active seasons was substantiated by observations of leaf quantity on trees at the Oneida site. The trees first began to be foliated at the end of March, were significantly leafed by mid-April, and were completely leafed by mid-May. Leaves began to fall very early (early July) but the trees still had significant leaf coverage through August. By early September, approximately 50% of the leaves had fallen and by October 8th nearly all of the leaves had fallen.

Examples of the Groundwater Recession Comparison method for MW6 are shown in Figure 5.8. This sequence was used to calculate direct transpiration rates from nearly the beginning of the active season until nearly the end. The durations used for the GRC method were limited to 72 hours since rainfall usually occurred within one to two days of the time of observation. All groundwater recessions were fitted with a ‘best-fit’ linear regression so that slopes could be determined. It was desired that R^2 values for the linear regression remain above 0.9, though this was not the case for both July and October. During periods when the water table elevations were relatively and consistently low, data recorded by the transducer at MW6 exhibited irregular fluctuations referred to as “noise”. This can be observed in Figures 5.3-5.4 when the water table elevation gets below 1426 feet. This problem was attributed to an aging sensor which was eventually replaced in August 2004. For the July regression data set, a 10-value running average was implemented to cut down on “noise” and achieve a linear regression. No other direct transpiration rates could be determined during for July due to a lack of data which could be used for comparison. In July 2004, the elevation of the water table falls below 1426 feet. Besides January 2001, no other dormant water table elevation data between 1426 and 1425.5 feet existed which was not interrupted by a rain event. In addition, a malfunction occurred on July 19, 2004 which caused the level logger to stop recording data. No water level data was recorded at MW6 between July 19th and August 9th during 2004.

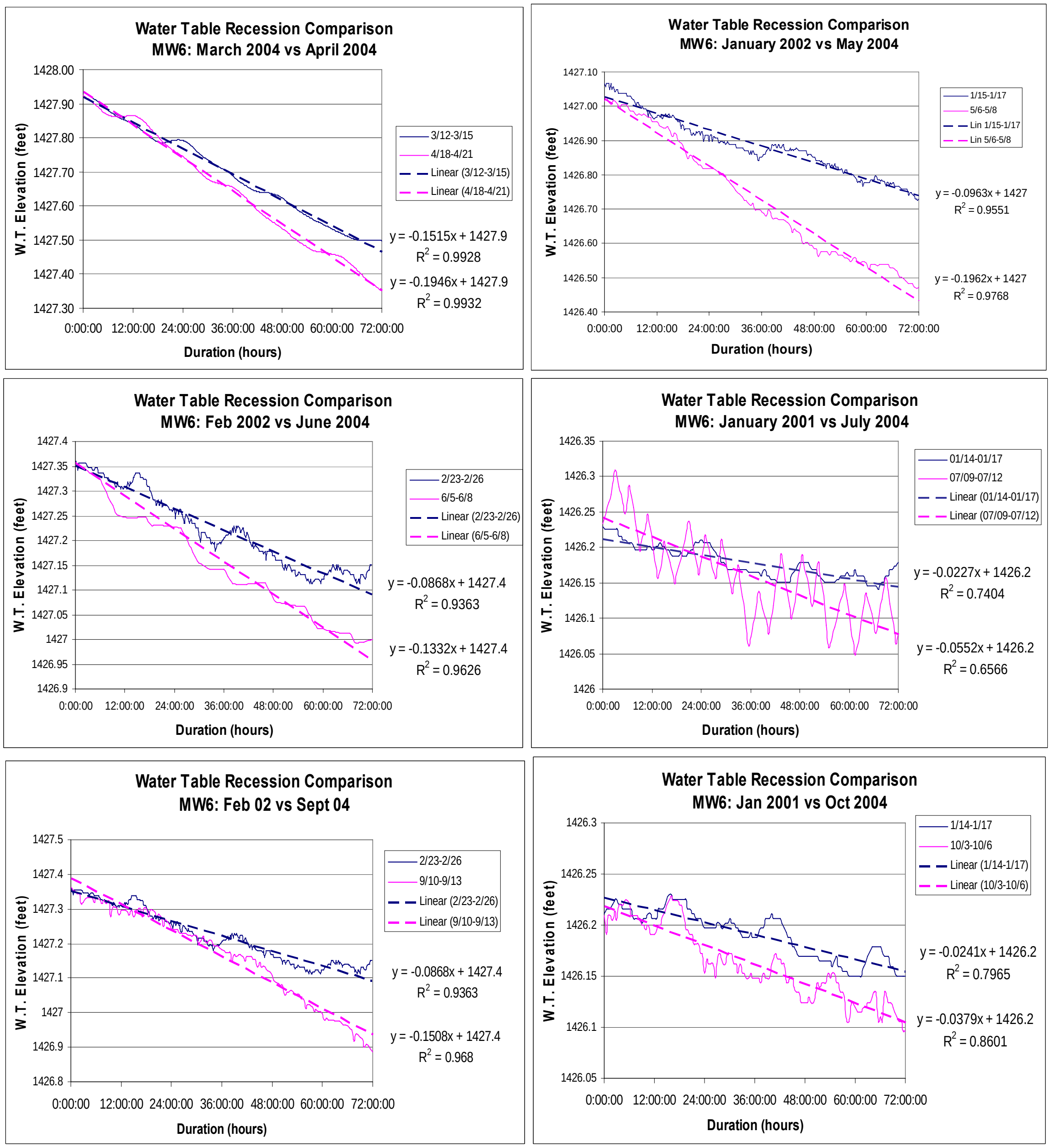


Figure 5.8 Groundwater Recession Comparison method series for MW6.

The Groundwater Recession Comparison method yielded twenty direct transpiration rates for the active season (Table 5.3). Direct transpiration values calculated via the GRC method ranged from 0.0028 to 0.0100 feet/day during the active season. For the purpose of comparison, three values were determined for the dormant season. Ideally, dormant season direct transpiration rates would be 0.00 feet/day since transpiration does not occur during this time when the trees have no leaves. The values calculated for dormant dates ranged from 0.0001 to 0.001 feet/day. This indicates that from a specific elevation, the water table does not recede at an absolutely consistent rate. However, it should be re-stated that the accuracy of the level logger is ±0.01 feet and that a slope difference of ±0.01 feet would result in the calculation of a direct transpiration rate of 0.001 feet/day. Thus, direct transpiration rates are only accurate to the nearest 0.001 feet/day.

Table 5.3 Direct transpiration rates, T_{DT} (feet/day) calculated for 2004 from observation points MW6, P4, and P25.

Well	Starting W.T. Elev (feet)	GW Recession A			GW Recession B			Difference (absolute)	T_{DT}
#		Year	Dormant Date	Avg Slope (ft/d)	Year	Active Date	Avg Slope (ft/d)		S_y=0.10 (feet/day)
MW6	1429.38	2001	19-Feb	-0.4301	2001	21-Feb	-0.4399	0.0098	0.0010
MW6	1427.91	2004	12-Mar	-0.1431	2004	23-Mar	-0.1477	0.0046	0.0005
MW6	1427.93	2004	12-Mar	-0.1515	2004	18-Apr	-0.1946	0.0431	0.0043
MW6	1427.03	2002	15-Jan	-0.0963	2004	6-May	-0.1962	0.0999	0.0100
MW6	1427.36	2002	23-Feb	-0.0868	2004	5-Jun	-0.1332	0.0464	0.0046
MW6	1426.23	2001	14-Jan	-0.0227	2004	9-Jul	-0.0552	0.0325	0.0033
MW6	1427.05	2002	15-Jan	-0.1075	2001	19-Aug	-0.1358	0.0283	0.0028
MW6	1427.36	2002	23-Feb	-0.0868	2004	10-Sep	-0.1508	0.0640	0.0064
MW6	1427.05	2002	15-Jan	-0.1075	2004	23-Sep	-0.1408	0.0333	0.0033
MW6	1426.23	2001	14-Jan	-0.0241	2004	3-Oct	-0.0379	0.0138	0.0014
MW6	1427.50	2001	6-Jan	-0.2065	2003	24-Dec	-0.2056	0.0009	0.0001
P4	1428.69	2004	13-Mar	-0.0508	2004	4-Apr	-0.0817	0.0309	0.0031
P4	1428.69	2004	13-Mar	-0.0508	2004	27-Apr	-0.0927	0.0419	0.0042
P4	1428.50	2004	26-Mar	-0.0640	2004	5-May	-0.1308	0.0668	0.0067
P4	1428.50	2004	26-Mar	-0.0617	2004	7-Jun	-0.0949	0.0332	0.0033
P4	1429.85	2001	22-Jan	-0.3039	2004	18-Sep	-0.3488	0.0449	0.0045
P4	1428.70	2004	24-Mar	-0.0720	2004	22-Sep	-0.1051	0.0331	0.0033
P4	1428.50	2004	24-Mar	-0.0640	2004	23-Sep	-0.1030	0.0390	0.0039
P25	1427.50	2004	8-Feb	-0.2013	2004	7-Mar	-0.2074	0.0061	0.0006
P25	1426.75	2004	13-Feb	-0.0612	2004	2-Apr	-0.0899	0.0287	0.0029
P25	1426.50	2004	16-Mar	-0.0255	2004	21-Apr	-0.1052	0.0797	0.0080
P25	1427.23	2004	10-Feb	-0.1335	2004	19-Sep	-0.1682	0.0347	0.0035
P25	1426.50	2004	16-Mar	-0.0255	2004	23-Sep	-0.0538	0.0283	0.0028

5.2.2 Results of White's Equation

The results of the application of White's equation to 2004 continuous water level records yielded only two values for direct transpiration. The primary reason is due to the lack of diurnal patterns observed during the active season. It is not known why diurnal patterns were so scarce at the Oneida site, but aquifer heterogeneity and depth to water may be influential factors. The Oneida site aquifer contains stratified layers of course and fine grained material. These different materials, found at different elevations within the aquifer, probably yield groundwater at different rates. For instance, if diurnal fluctuations were observed at a specific piezometer at an elevation where a course grained material was found, then diurnal fluctuations might not be observed at the same piezometer when the water table was within a layer of fine grained material. Figure 5.9 illustrate the results of applying White's Equation to Oneida water table data and Table 5.4 tabulates the results.

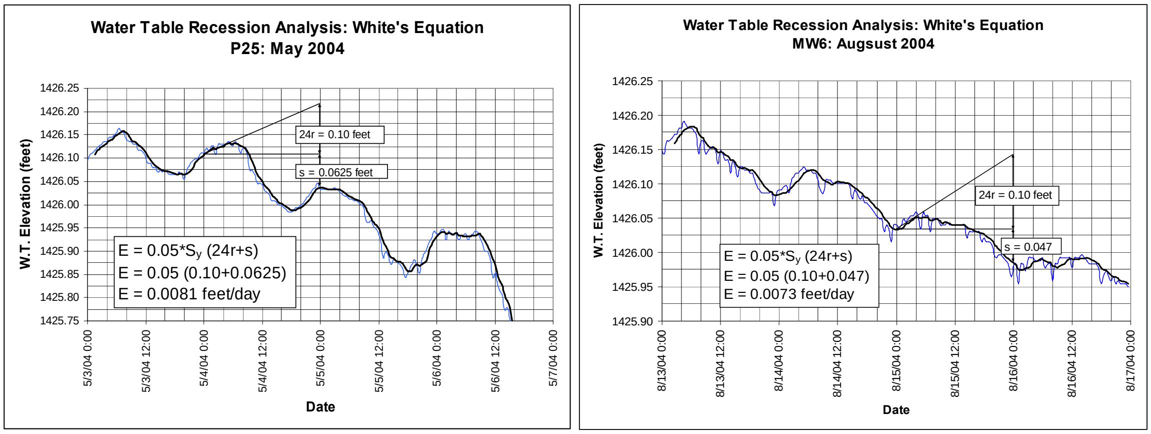


Figure 5.9 White's Equation applied to diurnal data from May and August 2004.

Table 5.4 Results of White's Equation at Oneida phytoremediation site, 2004.

Well #	Year	Day-Month	0.5*S_y	24r	s	T_{DT} (feet/day)
MW6	2004	14-Aug	0.05	0.1000	0.0467	0.0073
P25	2004	4-May	0.05	0.1000	0.0625	0.0081

5.2.3 *Saturated Thickness Estimation*

It is widely recognized that transpiration's impact on the saturated zone of an aquifer is dependent on the availability of water to plant roots (Vose 2003, Davis & Peck 1986). For this reason, the time trend of the saturated thickness of the aquifer underlying the study site was considered. Saturated thickness estimation is derived from monthly discrete water table elevation measurements (Table 5.2), average water table elevations recorded during each GRC method duration, and multilevel sampler data. The saturated thickness was determined by subtracting the estimated elevation of the confining layer of the aquifer from the average water table elevation at the same observation point. For this study, the elevation of the confining layer was considered to be equal to the recorded elevation for the base of the borehole of the closest multilevel sampler. It should be noted that the elevation of the confining layer at MW6 was estimated to be 1421.87' which is higher than the elevation of the bottom of the well casing (1419.62'). It is thought that the depth of MW6 penetrates the confining layer. A summary of saturated thicknesses from varying times and observation points is summarized in Table 5.5.

Table 5.5 Saturated thicknesses at MW6, P4, and P25 at varying points in time.

MW6 – 2003			P4 - 2003			P25 - 2004		
Bedrock Elev. = 1421.87 feet			Bedrock Elev. = 1422.90 feet			Bedrock Elev. = 1420.66 feet		
Date	WT Elev (feet)	Sat Thick (feet)	Date	WT Elev (feet)	Sat Thick (feet)	Date	WT Elev (feet)	Sat Thick (feet)
3/6/2004	1430.35	8.48	3/6/2004	1430.09	7.19	3/7/04	1427.20	6.54
3/23/2004	1427.91	6.04	4/4/2004	1428.53	5.63	4/2/04	1426.61	5.95
4/18/2004	1427.93	6.06	4/24/2004	1428.55	5.65	4/21/04	1426.34	5.68
4/24/2004	1427.07	5.20	4/27/2004	1428.52	5.62	4/28/04	1426.27	5.61
5/6/2004	1427.03	5.16	5/5/2004	1428.32	5.42	5/7/04	1425.89	5.23
5/24/2004	1426.93	5.06	5/24/2004	1427.30	4.40	8/9/04	1425.44	4.78
6/6/2004	1427.08	5.21	6/7/2004	1428.35	5.45	8/29/04	1425.53	4.87
6/15/2004	1426.49	4.62	6/15/2004	1428.02	5.12	9/23/04	1426.40	5.74
7/10/2004	1426.16	4.29	7/6/2004	1427.55	4.65			
8/9/2004	1426.16	4.29	8/9/2004	1427.56	4.66			
8/19/2004	1426.81	4.94	9/3/2004	1427.00	4.10			
9/3/2004	1425.99	4.12	9/18/2004	1429.30	6.40			
9/10/2004	1427.16	5.29	9/22/2004	1428.40	5.50			
9/23/2004	1426.85	4.98	10/8/2004	1427.34	4.44			
10/8/2004	1426.16	4.29						

5.2.4 Time Trend of Direct Transpiration Rates and Saturated Thickness

The values for direct transpiration determined by the GRC method and White's equation from each observation point show similar trends between March and October 2004. The first three graphs in Figure 5.10 illustrate the time trend of direct transpiration rates and saturated thickness using data from each observation point. The last graph compares the time trend of direct transpiration rates recorded at all three observation points.

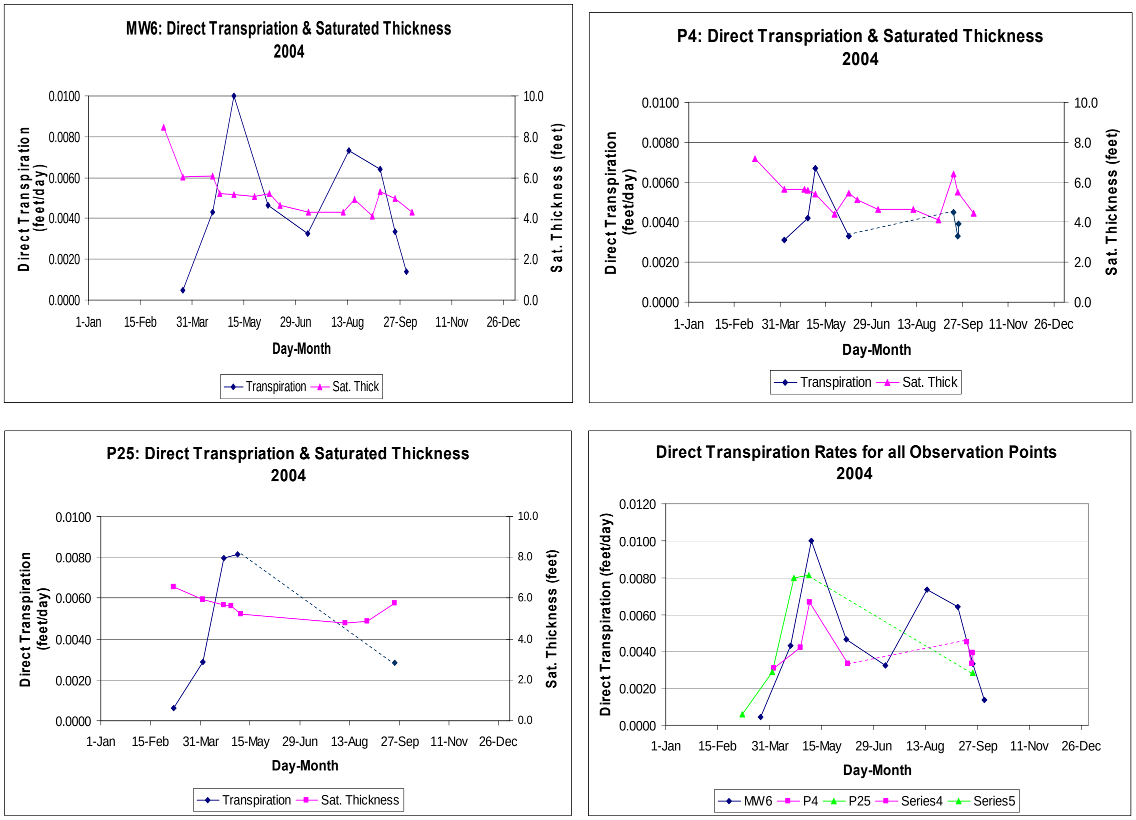


Figure 5.10 Time trend of 2004 direct transpiration rates and average saturated thickness (H) for observation points MW6, P4, and P25.

As shown in Figure 5.10, direct transpiration rates are relatively low during the early spring but then begin to increase through late spring. This is logical considering the trees were barely leafed at the start of spring. Conversely, the saturated thickness starts relatively high in the early spring but then begins to decrease. During that period, the trees become foliated and cause the seasonal sink for groundwater which in turn causes the increased rate of recession of the water table. During early and mid-summer, transpiration rates decrease and the saturated thickness remains relatively low and steady.

It is not known exactly why there is downward trend in direct transpiration at a time when it seems like it would be at its peak (mid-summer). One explanation is the decreasing thickness of the saturated zone and the increasing depth to the water table impedes the ability of the hybrid poplar trees to utilize groundwater from the saturated zone. This explanation is supported by observations made regarding tree stress. As mentioned in Chapter 2, tree stress may be inflicted by groundwater level decline and is exhibited by a decrease in leaf area (aka: loss of leaves). This loss of leaves is a response to the inability of the leaves to transpire the amount driven by the vapor pressure deficit. Field observations from July 7, 2004 note that the poplar trees at Oneida had already begun to lose many leaves. Though the canopy still appeared relatively full, there were a significant number of leaves accumulated on the land surface. During August and/or September, both transpiration rates and the saturated thickness increase for observation made at MW6, P4, and P25. This dual increase suggests that saturated thickness influences direct transpiration rates. Toward the tail end of summer and the beginning of fall, direct transpiration and saturated thickness appear to be less related; perhaps due the observed loss of leaves by October 8, 2004 (nearly 90% of leaves had fallen). Overall, direct transpiration rates at the Oneida phytoremediation site were highest in late spring with a maximum rate of 0.010 feet/day at MW6.

Direct transpiration rates vary with time for a variety of reasons including local weather changes, time of season, and depth to groundwater or saturated thickness. It seems logical that when conditions are the same, transpiration rates across the site are also similar. Since site conditions are time dependent, comparisons of direct transpiration rates between different points of observation can only occur on the same day. At the Oneida site, September 23, 2004 was the only day when direct transpiration rates were calculated for all three observation points. On that day, direct transpiration rates which were quantified from all three observation points did show some variability (Figure 5.11). The direct transpiration rate recorded at P4 was the highest at 0.0039 feet/day while MW6 and P25 were recorded to be 0.0033 and 0.0028 feet/day, respectively. The difference between P4 and P25 direct transpiration rates on that day was 0.0011 feet/day.

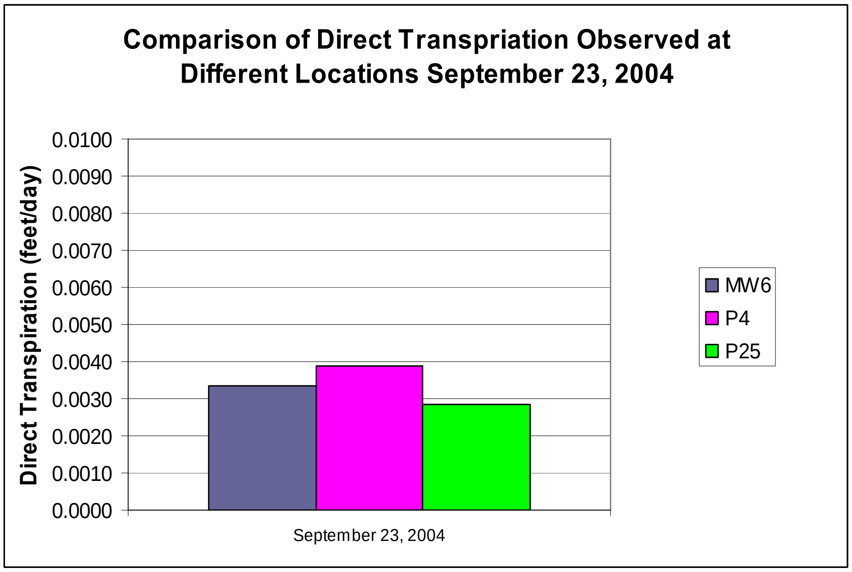


Figure 5.11 September 23, 2004 T_{DT} comparison.

5.2.5 Comparison of Direct Transpiration Rates to Past Results

With regard to past data, Panhorst (2000) quantified transpiration rates during August and September 1999 using the GRC method and White's Equation. Illustrated in Figure 5.12, the comparison between 1999 and 2004 transpiration rates shows that 2004 rates were consistently higher. The difference between transpiration rates calculated for August/September 2004 and August/September 1999 seems logical when considering the amount of tree growth that occurred during the five-year span.

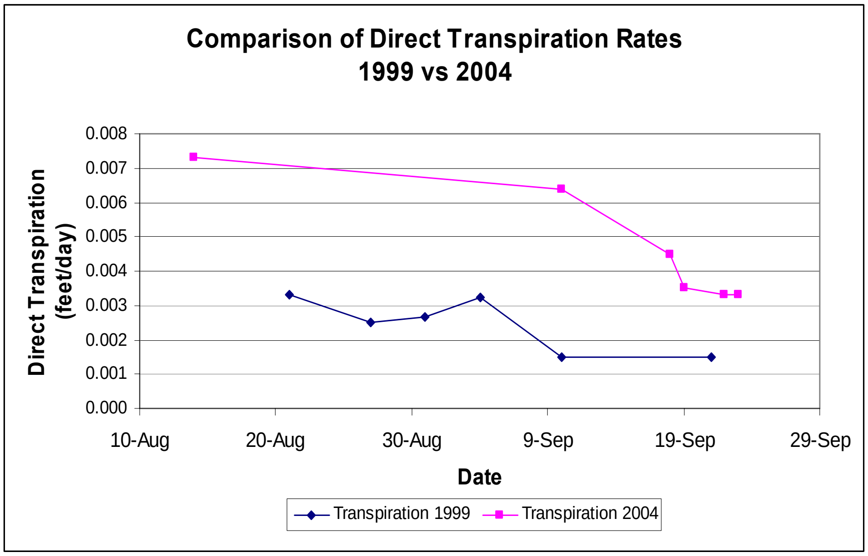


Figure 5.12 2004 T_{DT} versus 1999 T_{DT}.

Panhorst (2000) also performed a simple water budget for the Oneida phytoremediation site using hydrologic data from 1998. The results of this water budget yielded monthly volumetric evapotranspiration rates for a 1.67 acre area which comprised the Oneida phytoremediation system and part of its surrounding area. When divided by the area of the site (72,745.2 square feet), Panhorst's values yield a time trend of evapotranspiration rates which can be compared to direct transpiration rates calculated for 2004. This comparison is illustrated in Figure 5.13.

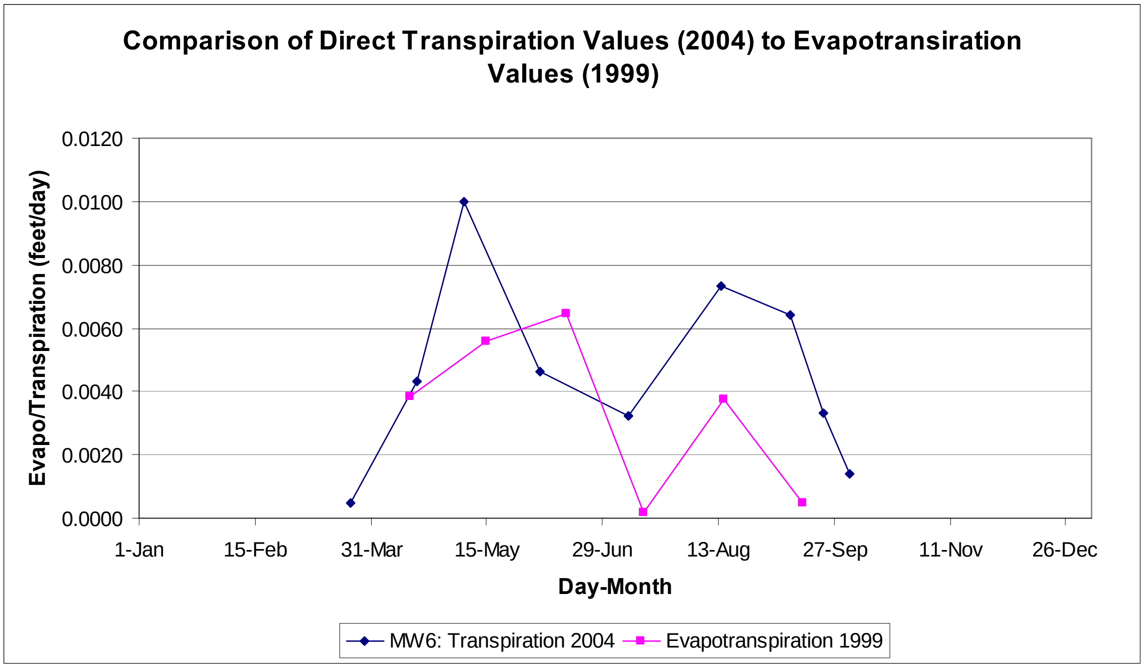


Figure 5.13 Comparison of 2004 T_{DT} to 1999 ET.

The comparison between direct transpiration values calculated for the 2004 active season and evapotranspiration values calculated for the 1999 season yields two primary observations: 1) the transpiration time trends of water are similar in that there is an increase between early spring and late spring, there is a decrease of water lost from the site in mid-summer, an increase towards late summer, and a final decrease towards the end of the active season; 2) the rate of water lost from the site during 1999 is consistently lower than the rate lost from the site during 2004. With regard to first point, the time trend of transpiration seems to agree with rainfall trends at the Oneida site. During the early spring there are typically many rain events, during early summer there is a dry period, there second wet period in late summer, and finally dry weather during early fall.

As illustrated in Figures 5.3-5.7, rainfall is directly related to saturated thickness. With regard to the second point, if the rate of water lost is directly related to direct transpiration by the hybrid poplar trees, it is logical that there was an increase in [evapo]transpiration rates since there was tree growth between 1999 and 2004. Tree diameter has been directly correlated with transpiration rates (Vose 2003, Calder 1993).

Corack (2000) also estimated the total volume of evapotranspiration from the site using a detailed water budget analysis. Corack estimated the total volume of water lost due to evapotranspiration from the site was equal to 141,800 ft^3 during May 1999. The area modeled was equal to 403,180 ft^2. The daily evapotranspiration rate for the month of May is determined by the following:

$$Q_{ET}\left(\frac{ft^3}{day}\right) = \frac{V_{ET(May)}\,ft^3}{\#\,days} = \frac{141{,}000\,ft^3}{31 days} = 4548.4\frac{ft^3}{day}$$

$$ET_{May}\left(\frac{ft}{day}\right) = \frac{Q_{ET}\left(\frac{ft^3}{day}\right)}{A\left(ft^2\right)} = \frac{4548.4\frac{ft^3}{day}}{403{,}180\,ft^2} = 0.0113\frac{ft}{day}$$

The direct transpiration rates quantified for the month of May in 2004 were determined by both the Groundwater Recession Comparison Method (MW6, P4) and White’s Equation (P25). The direct transpiration rates determined during the month of May for MW6, P4, and P25 are 0.0100, 0.0067, and 0.0081 feet/day, respectively. The average of all of these values is 0.0083 feet/day. This value for direct transpiration is slightly lower than the value of evapotranspiration determined by Corack (2000). This is logical considering the value of evapotranspiration calculated by Corack included all water both evaporated and transpired from the entire aquifer over the 403,180 ft^3, including both the saturated and vadose zones underlying the roughly 1-acre phytoremediation system. This difference is logical considering the total ET should always be greater than direct transpiration. However, it is evident from the calculation of direct transpiration in 2004 that direct transpiration is the dominant quantity within the ET value. It should be noted that the average value of evapotranspiration reported by Corack for the entire growing season of 1999 was 0.0041 feet/day while for 2004 is was

0.0048 feet/day. This is also logical considering the trees grew significantly, thus increasing the rate of direct transpiration, during that time period.

5.2.6 Comparison of Direct Transpiration at Oneida to Other Sites

In general, direct transpiration rates observed at the Oneida phytoremediation site agreed with transpiration rates observed at other sites which included hybrid poplar stands and hybrid poplar phytoremediation systems. For example, transpiration measurements at a poplar stand in Flanders, Belgium yielded a daily maximum and mean of 0.0164 and 0.0062 feet/day, respectively, between April 1st and October 31st (Meiresonne et al, 1999). At the Oneida site, the daily maximum and mean observed was 0.0100 and 0.0048 feet/day, respectively. Poplar trees found at the Belgium site were 13 years old at the time of measurement, while at the Oneida site the trees were approximately 9 years old. The majority of the trees found at the Belgium site had a DBH of over one foot, while at Oneida the majority of the trees had a DBH between 0.10 and 0.40 feet. Trees at Oneida were spaced much closer than at the site in Belgium, 3 feet x 10 feet versus 23 feet x 24.6 feet, respectively.

Mid-summer transpiration rates for poplar based phytoremediation systems in Texas, Colorado, and Florida were reported to be 0.0033, 0.0014, and 0.0062 feet/day (Vose et al, 2003). At Oneida, mid-summer rates quantified from MW6 data (July and August) were 0.0033 and 0.0073 feet/day respectively.

5.3 Estimation of Volumetric Direct Transpiration Rates

5.3.1 Results of Individual Tree Volumetric Transpiration Rates

The results of applying direct transpiration rates to representative areas surrounding observation points MW6, P4, and P25 yielded individual volumetric direct transpiration rates for 164 trees found within the three 900 and 2500 square-foot representative areas. Using these volumetric direct transpiration rates from each representative area, per tree volumetric direct transpiration rates (Q^{T}_{DT}) were calculated as shown in the example calculation in Table 4.3. Plots of per tree volumetric direct transpiration for all of the 164 trees are shown in Appendix E.

5.3.2 Variation of the k-value

When plotted, values of per tree volumetric direct transpiration from each representative area (900 and 2500 square-foot) versus tree diameter yield a *k*-value from the power equation: $Q^{T}_{DT} = kx^{2}$ where x is the tree diameter and the units of coefficient *k* are gal-ft/ft^{3}-day so as to yield gallons/day using DBH in units of feet. A series of plots showing the distribution of T_{DT} values over a 900 square-foot area containing 19 trees for MW6 from April through October 2004 is shown in Figures 5.14.

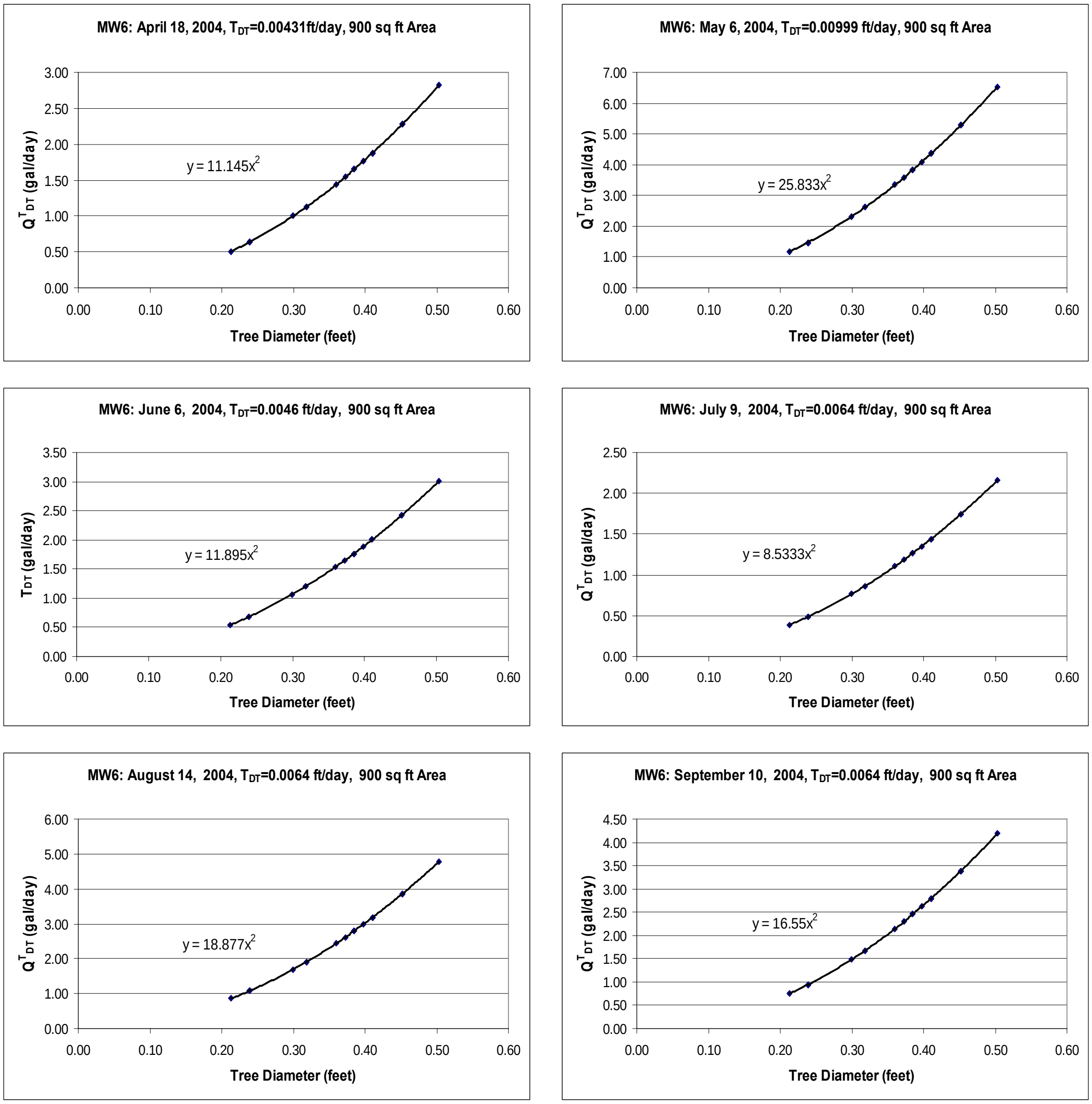


Figure 5.14 Series of per tree volumetric direct transpiration versus tree diameter plots of trees within 900 ft^{2} area surrounding MW6.

The application of all direct transpiration rates from all observation points to 900 and 2500 square-foot representative areas yielded 44 *k*-values (Table 5.6). During 2004, *k*-values ranged from 1.39 to 39.03 gal-ft/ft^3-day.

Table 5.6 Tabulated *k*-values resulting from the application of direct transpiration rates to trees within representative areas surrounding observation points MW6, P4, and P25.

Observation Point #	Date	T_{DT} (feet/day)	Representative Area: 900 ft^2 k	Representative Area: 2500 ft^2 k
MW6	3/23/04	0.0005	1.290	1.478
MW6	4/18/04	0.0043	11.145	13.850
MW6	5/6/04	0.0100	25.830	32.103
MW6	6/5/04	0.0046	11.895	14.782
MW6	7/9/04	0.0033	8.533	10.605
MW6	8/14/04	0.0073	18.877	23.459
MW6	9/10/04	0.0064	16.550	20.567
MW6	9/23/04	0.0033	8.533	10.605
MW6	10/3/04	0.0014	3.620	4.499
P4	4/4/04	0.0001	13.024	15.585
P4	4/27/04	0.0042	17.661	21.133
P4	5/5/04	0.0067	28.114	33.692
P4	6/7/04	0.0033	13.909	16.745
P4	9/18/04	0.0045	18.925	19.671
P4	9/22/04	0.0033	13.909	16.644
P4	9/23/04	0.0039	16.438	19.671
P25	3/7/04	0.0006	2.940	2.321
P25	4/2/04	0.0029	14.055	11.103
P25	4/21/04	0.0080	39.031	30.832
P25	5/4/04	0.0081	38.198	30.175
P25	9/19/04	0.0035	16.993	13.424
P25	9/23/04	0.0028	13.712	10.832

Since *k*-values are based on direct transpiration rates (feet/day) quantified by the GRC method and White's Equation, the time trend of *k*-values is similar to the time trend for T_{DT} values. Values of *k* were calculated at all observation points (MW6, P4, and P25) for both 900 and 2500 square-foot representative areas. In general (73%), values of *k* determined using a 2500 square-foot representative area were larger than *k*-values determined using a 900 square-foot representative area. This difference can be attributed to variation in the number of trees per unit area. As the number of trees per unit area increases for a specified representative area, the value of *k* decreases. Conversely, as the number of trees per unit area decreases for the same sized representative area, the value of *k* increases. For instance, if the representative area was increased to 100,000 square feet for all observation points, the representative area would contain all of the trees within the phytoremediation system. Keeping in mind that volumetric transpiration is directly proportional to land area ($Q_{DT} = T_{DT} \times A$), if the representative area continued to grow, the number of poplar trees within the area would remain the same (finite number of poplars), which would result in infinitely growing *k*-value. This leads to the question: what representative area with what number of trees per unit area best represents the Oneida phytoremediation site? That questioned can only be answered when the boundaries of the phytoremediation site are determined. This study overlaid a 40,000 square foot grid to encompass the portion of the phytoremediation site which contains the contaminant plume. Within the grid, the number of trees per square foot ranged from approximately 0 to 0.05. The number of trees per square foot for the representative areas used around each observation point is shown in Table 5.7.

Table 5.7 Number of trees per square foot within representative areas surrounding each observation point.

Observation Point	Representative Area	
	900 sq-ft # trees/sq-ft	2500 sq-ft # trees/sq-ft
MW6	0.0211	0.0172
P4	0.0244	0.0252
P25	0.022	0.0232

The values shown in Table 5.7 are in good agreement with the average number of trees per square foot found at the Oneida phytoremediation site, however the value for MW6 using a 2500 square-foot area was somewhat low. This was expected because there are fewer trees surrounding MW6. The number of trees per unit area surrounding MW6 is lower because a portion of its 2500 square-foot area is occupied by the oil-water separator and thus not planted.

With the assumption that the number of the trees found within the representative areas surrounding each observation point are indicative of the entire site, the *k*-values were lumped together so that an overall time trend of volumetric direct transpiration could be observed. Figure 5.15 illustrates the time trend of *k*-values for both representative areas using *k*-values calculated at all observation points during 2004. The *k*-values are plotted with saturated thickness values determined from discrete water level measurements and the average of continuous water levels observed during the calculation of T_{DT}.

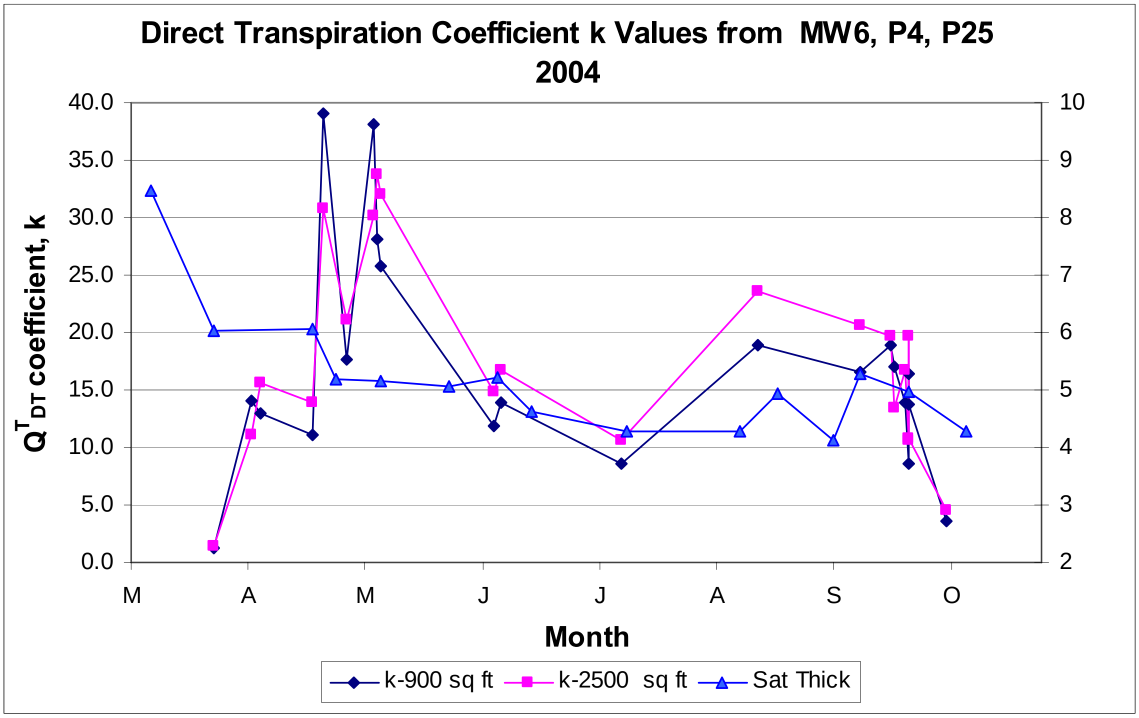


Figure 5.15 Time trend of k-values from all observation points during 2004.

Since *k*-values are proportional to direct transpiration rates (feet/day), the time trend is similar. Plotting *k*-values for both the 900 and 2500 square-foot representative areas provided a range of *k*-values which can be applied to the entire phytoremediation system to determine the volumetric direct transpiration of the system on a per tree basis. The sum of the per tree volumetric transpiration rates will indicate the total volumetric direct transpiration rate for the system.

5.3.3 *Application of the k-value to Study Site Poplar Trees*

Based on Figure 5.15, if the average *k*-value (900 and 2500 square feet) on a per month basis is applied to all of the trees of the phytoremediation system, a range of per tree volumetric transpiration rates on a monthly basis can be established. Figure 5.16 illustrates the distribution of volumetric transpiration over the range of tree sizes found at the Oneida site on a monthly basis. During the month of peak transpiration (May), the per tree volumetric direct transpiration values range from 0.26 gallons/day to just over 13 gallons/day during times of peak transpiration. During early October, the period of lowest transpiration, the values ranged from 0.03 to 1.56 gallons/day. The large range of per tree volumetric direct transpiration rates is attributed to the large range of tree diameters found on-site.

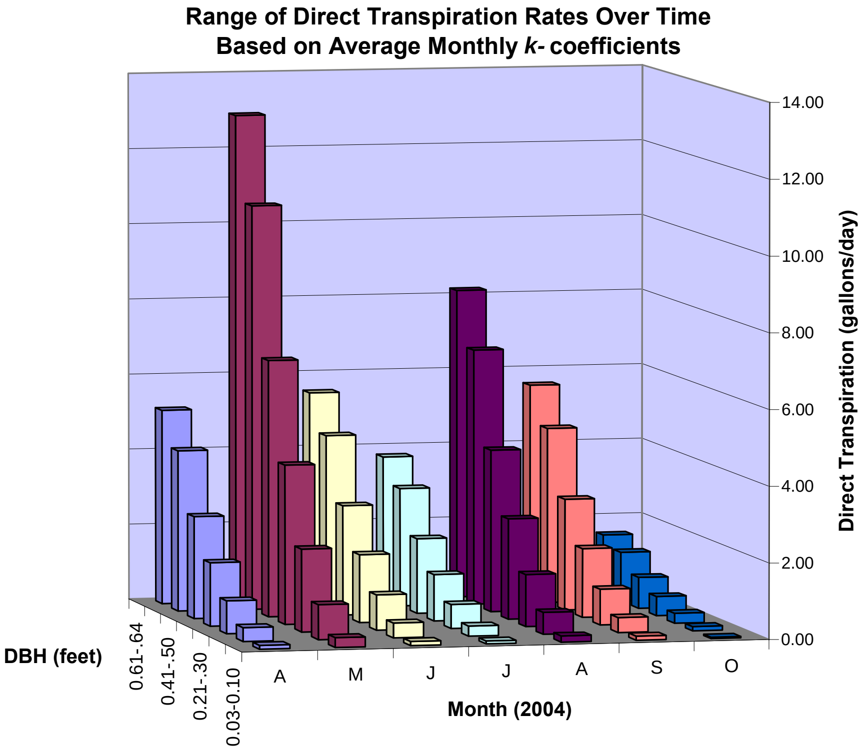


Figure 5.16 Distribution of volumetric direct transpiration over time based on DBH.

While the amount of water transpired by trees which are greater than 0.5 feet in diameter looks significant, it should be noted that the percentage of trees within this group is fewer than 2%. Trees which range from 0.21-0.30 feet in diameter make up 38% of this site, followed by range of 0.11-0.20 feet and 0.31-0.40 feet which make up

31.3% and 19.5%, respectively, of tree diameters on site. With regard to Figure 5.16, if more of the trees were able to grow to their maximum potential, then the volumetric rate of water directly transpired from the site would increase considerably.

5.3.4 Comparison of Volumetric Direct Transpiration to Past Results

In 2003, Corack calculated evapotranspiration for 1998 using the MODFLOW's ET package within GMS. Over an 8.5 day period for an area containing sixty trees Corack calculated a minimum (based on the average of 60 trees) transpiration rate of 0.4 gallons/day-tree and a maximum rate of 5.3 gallons/day-trees. This range of per tree transpiration rates by Corack is in good agreement with the rates determined in this study.

5.3.5 Comparison of Volumetric Direct Transpiration at Oneida to Other Sites

In general, volumetric direct transpiration rates estimated for the Oneida phytoremediation site agreed with volumetric transpiration rates quantified at other sites. At a phytoremediation system in Ogden, Utah, daily average volumetric transpiration rates resulting from 3-year old hybrid poplar trees was 449 gallons/day (Ferro et al, 2001). Based on observed direct transpiration rates, the average volumetric direct transpiration rate during 2004 at the Oneida site was estimated at 741 gallons/day. Though the Oneida site value seems significant in comparison, the Ogden, Utah site had only 25% as many trees as the Oneida site. Based on sap flow data, the Aberdeen, Maryland site reported an average 1090 gallons/day an area which contained 171 hybrid poplars. It should be noted that sap flow includes all water transpired from both the vadose and saturated zone of an aquifer, while direct transpiration rates only pertain to water from the saturated zone.

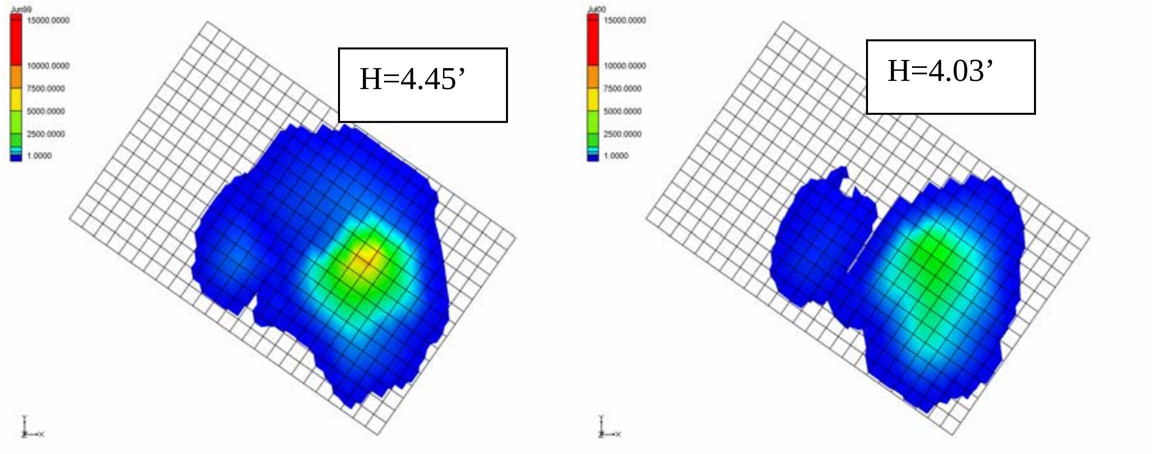
When the total daily volumetric transpiration rate is simply divided by the number of living trees at the Oneida site, the average value for transpiration appears low (1.2 gallons/day-tree). However, it should be noted that many of the trees at Oneida have very small diameters despite their age. The variation in tree diameter at Oneida ranges from 0.03 feet to 0.64 feet, with the majority of the trees falling within the lower half of that range. This relatively significant variation can probably be attributed to the relatively tight spacing of the poplar trees at Oneida. Being a competitive species, the larger poplar trees at the study site have thrived while smaller trees have grown very little. As previously stated, a majority of the trees at Oneida have to grown to their full potential, thus they do not directly transpire as much water as they potentially could.

5.4 Plant Uptake Rates of Naphthalene

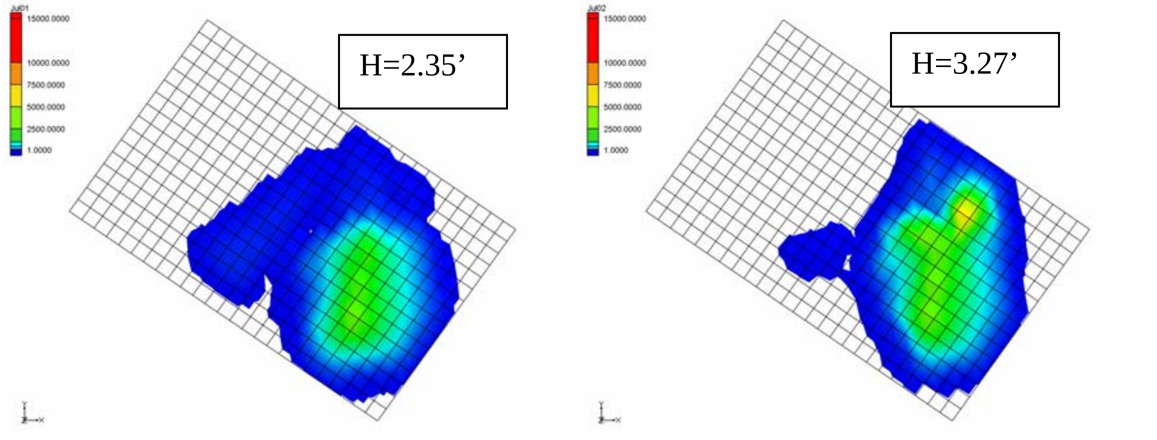
Plant uptake rates of naphthalene were calculated by applying per tree volumetric transpiration rates to naphthalene concentrations found in groundwater located in the upper portion of the saturated zone. As described in Chapter 4, the concentration of naphthalene found in this portion of the saturated zone was determined in two ways:
1) using the concentration of naphthalene in groundwater taken from the upper-most port of the multilevel samplers and 2) using the concentration of naphthalene calculated by averaging naphthalene concentrations in groundwater taken from the upper two ports of each multilevel sampler. This resulted in naphthalene concentrations for groundwater found in the upper one foot and upper 1.5 feet of the saturated zone.

5.4.1 Time Trend of Groundwater Concentrations of Naphthalene

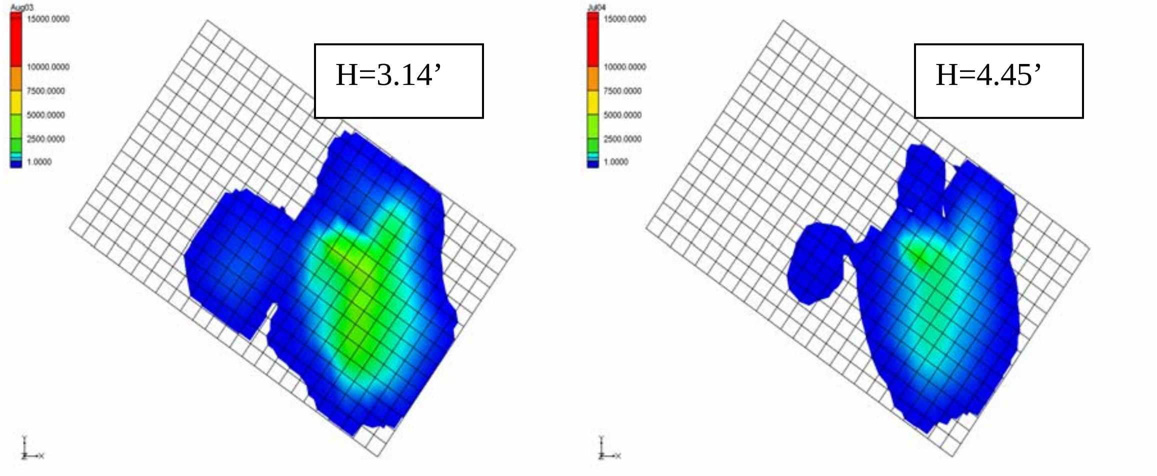
Since the thickness of the saturated zone is dynamic, the elevation of the concentration of naphthalene found in the upper 1-1.5-foot of the saturated thickness is variable over time. Because the contaminant is a DNAPL, the concentration of naphthalene in the upper 1-1.5 feet of the saturated thickness is relatively high when the water table elevation is low and relatively low when the water table elevation is high. To observe a time trend for the naphthalene plume, the time periods compared must have similar saturated thicknesses. For instance, it is not logical to compare the concentration of naphthalene found in the upper portion of the saturated thickness for day in March when the saturated thickness is six feet to a day in July or August when the saturated thickness is three feet. The concentration found in July would almost always be higher than that observed for March. For this reason, as illustrated by the Figures 5.17 and 5.18, sampling dates from mid-summer (usually July) were used to observe the time trend of the naphthalene plume. The average saturated thickness (H) near the time of the observation is noted at the top of each figure.



June 1999 **July 2000**

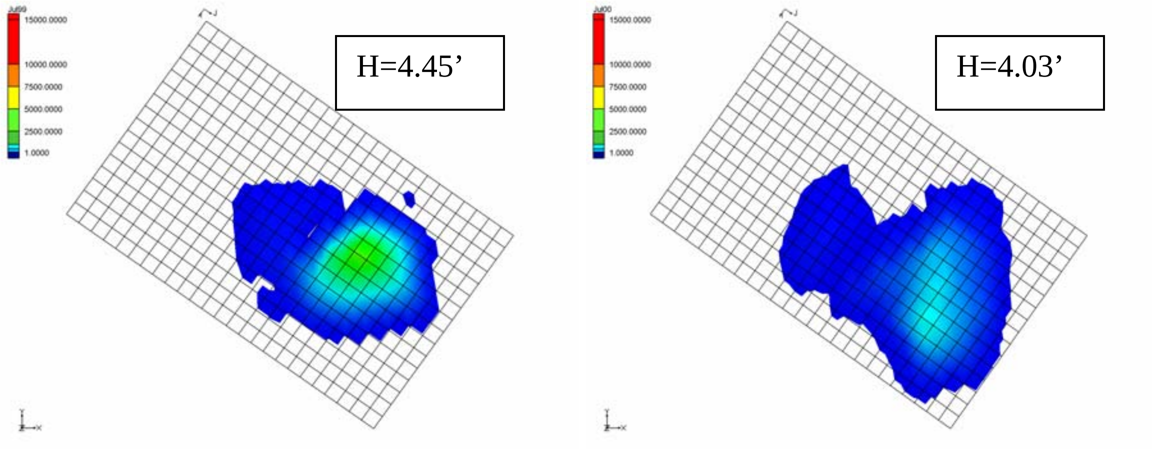


July 2001 **July 2002**

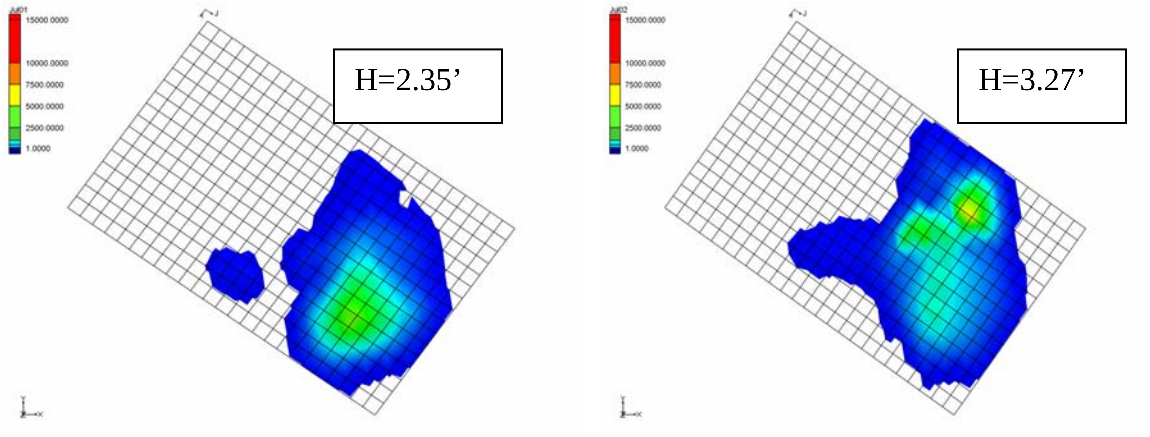


August 2003 **July 2004**

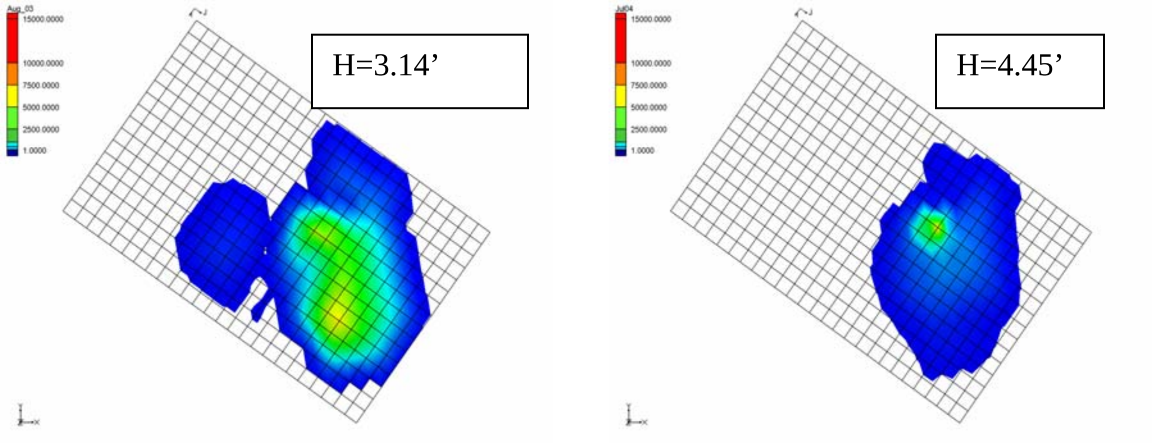
Figure 5.17 Concentrations determined by averaging concentrations measured from the top 2 ports of each multilevel sampler.



June 1999 **July 2000**



July 2001 **July 2002**



August 2003 **July 2004**

Figure 5.18 Concentrations measured from top port of each multilevel samplers.

When the concentrations from the multilevel sampler locations were linearly interpolated by GMS, a concentration was assigned to each cell. When averaged over the entire grid, these concentrations were plotted to observe the time trend of naphthalene concentrations found in the upper portion of the saturated thickness. Figure 5.19 illustrates a comparison between the average concentration of all the cells determined from samples taken from the top port of each multilevel sampler and the average concentration from samples derived from the top two ports of each multilevel sampler. It can be observed from the comparisons shown in Figure 5.19 that the average of the concentrations of naphthalene sampled from the upper two ports of the multilevel samplers are consistently greater than the concentration of naphthalene sampled from only the top port of the multilevel samplers. This difference is logical considering the DNAPL, the source of the naphthalene, primarily exists on the bottom of the aquifer.

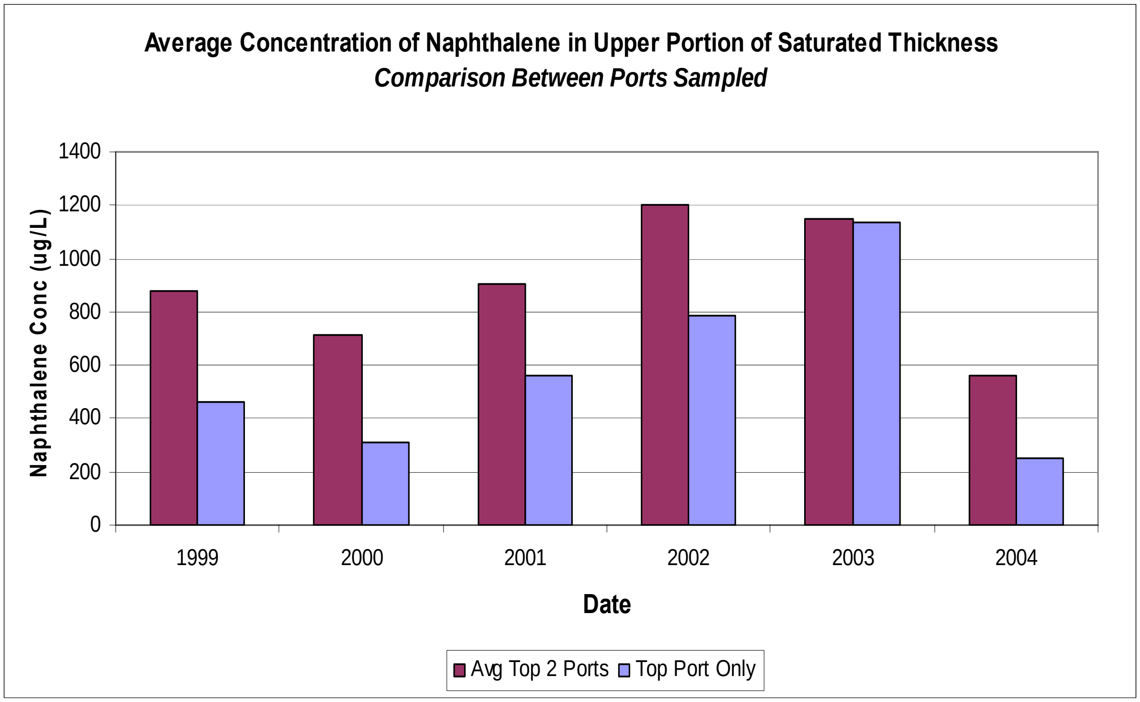


Figure 5.19 Comparison of the average of the top two ports versus the top port only.

One of the objectives of this study is to determine the mass removal rate of naphthalene from the groundwater underlying the study site. Using the concentration of naphthalene found in each cell, the mass of naphthalene found in the upper 1-1.5 feet of the saturated thickness was calculated by multiplying by the assumed porosity (n=0.3) and the volume of the cell. For concentrations determined using the top port of the multilevel samplers, the volume of each cell is considered to be 10’x10’x1’. For concentrations determined using the average of samples derived from the top two ports of the multilevel samplers, the volume of each cell is considered to be 10’x10’x1.5’. The time trend of naphthalene mass was plotted in order to observe the way the naphthalene mass found in the upper portion of the aquifer changes over time. Since saturated thickness is related to the amount of naphthalene mass found in the uppermost portion of the saturated zone, the time trend of saturated thickness was plotted on the same chart. Due to the lack of consistent discrete water level measurements or continuous water levels between 1999 and 2004, saturated thickness was determined by subtracting the elevation of the aquitard below each multilevel sampler from the elevation of the uppermost port sampled. These values were averaged to yield an overall value for saturated thickness. The change of naphthalene mass found in the uppermost portion of the saturated zone is plotted with average saturated thickness in Figures 5.20 and 5.21.

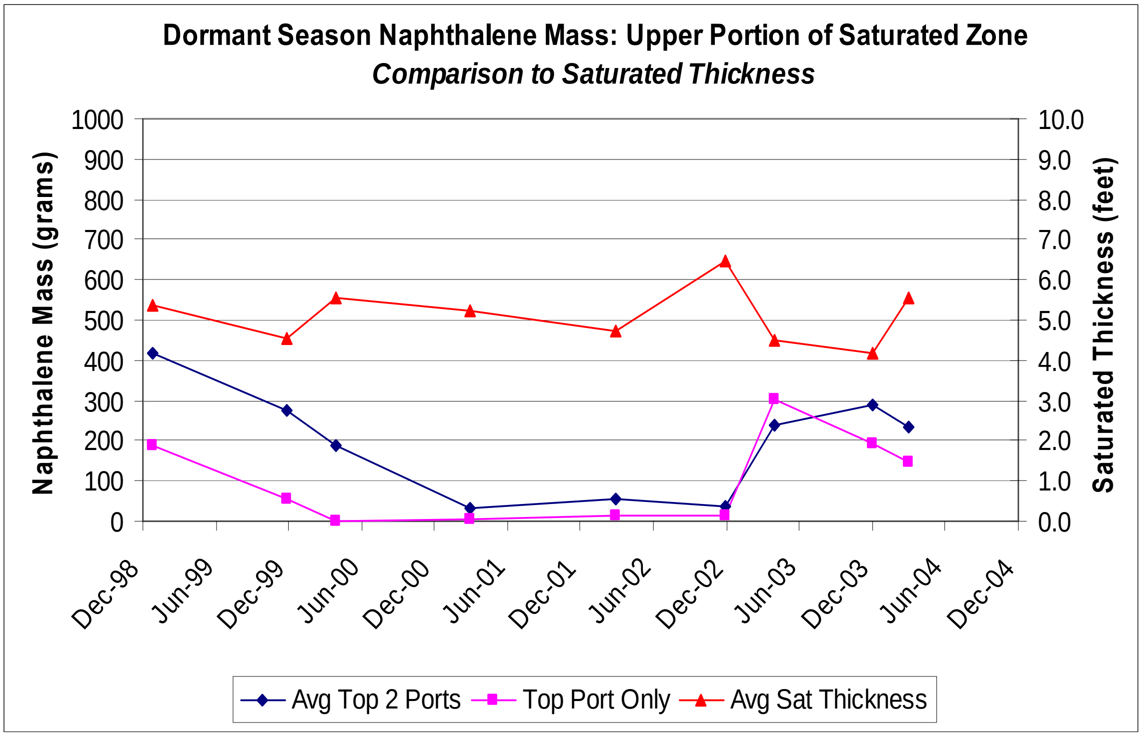


Figure 5.20 Dormant season naphthalene mass compared with average saturated thickness.

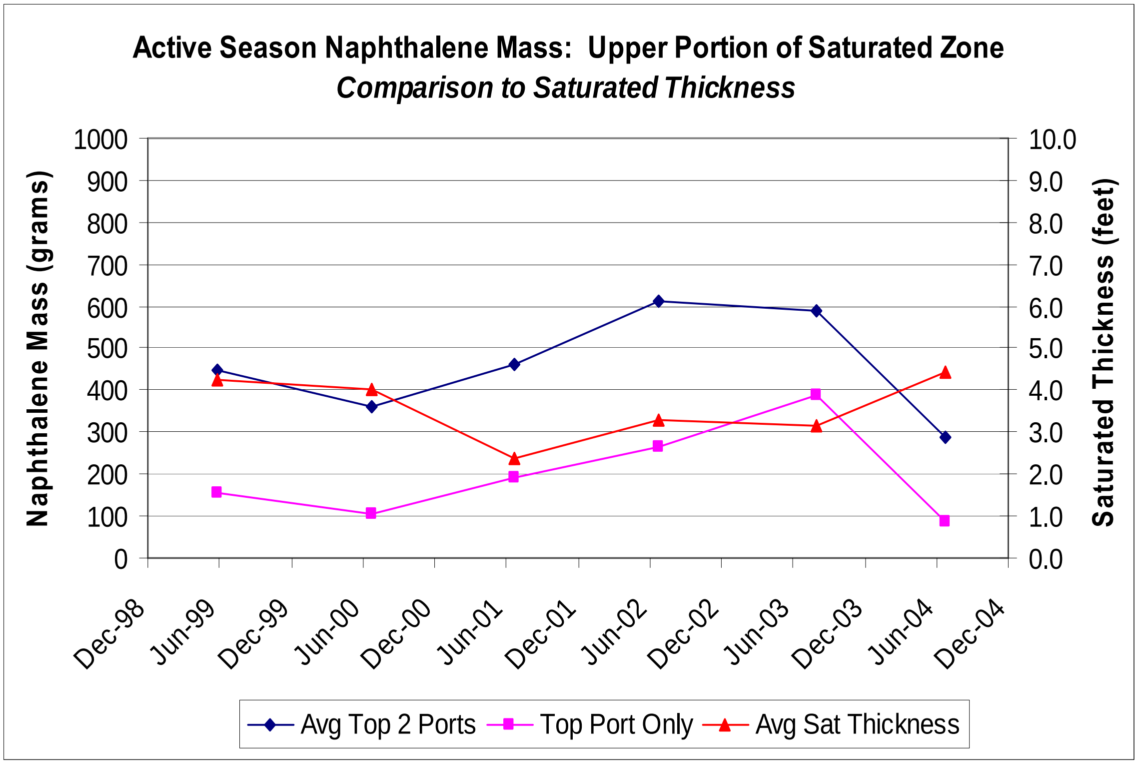


Figure 5.21 Active season naphthalene mass compared with average saturated thickness.

Figures 5.20 suggests that during dormant months, when the water table is presumably high due to recharge and lack of transpiration, the mass of naphthalene observed in the uppermost portion of the saturated zone is relatively low. Conversely, during the active months shown in Figure 5.21, when the water table is generally lower than in dormant months, the concentration in the upper portion of the saturated zone is relatively high. It is logical that the amount of naphthalene present in groundwater is higher when the water table is lower since the source of the contaminant is closer to the bottom of the aquifer. However, when observing summer months, Figure 5.21 show that naphthalene mass found in the upper portion of the aquifer increases over time. This variation could be attributed to an increase in direct transpiration over time. The effect of direct transpiration from the saturated zone could create an upward flux of naphthalene towards the upper portion of the aquifer. If this is true, then it seems logical that the rate of naphthalene mass removal increase over time.

Depending on one’s perspective, an increase in naphthalene mass within the upper portion of the saturated zone over time is not necessarily a desired trend with regard to contaminant attenuation. However, if trees on site are directly transpiring contaminated groundwater from upper portion of the saturate thickness and the mass of naphthalene within that portion of the saturated thickness is increasing, then the mass removal of naphthalene is increasing over time. This indicates an increased attenuation rate for naphthalene removal from the subsurface.

With regard to this study, one problem with time trends is that they do not always portray an accurate picture of what might actually be happening. For instance, concentration data were generally measured on a bi-annual basis. Since determination of the average saturated thickness is dependent on the elevation of the uppermost port sampled from each multilevel sampler, the only “snapshots” in time for which saturated thickness data are the same days which groundwater was sampled. It can be assumed that the dissolution of naphthalene from the DNAPL to groundwater does not happen all at once, but over time period during which the magnitude of the saturated thickness often changes. It can be observed from groundwater data that the saturated thickness is subject to numerous fluctuations due to recharge events. During these recharge events the groundwater table rises and subsequently falls. These fluctuations assumedly change the spatial location of naphthalene mass to some degree. Since recharge to the aquifer is a direct result of rainfall events, the mass of naphthalene was compared to yearly rainfall totals in Figures 5.22 and 5.23.

It can be observed in Figure 5.22 that the trend of yearly rainfall and naphthalene mass in the upper portion of the saturated thickness both decrease over time. The mass of naphthalene then remains relatively constant until 2003 when an increase occurs. During the same time period, below average rainfall gradually returns to average in 2002 and then exceeds average in 2003. Figure 5.23 suggests similar trends, but the correlation between the mass of naphthalene found in the upper portion of the saturated thickness and yearly rainfall totals is much more pronounced. It can be assumed that the more often rain events occur, the more water fluctuations occur. This increase in water fluctuations may increase the dissolution rate of naphthalene from the DNAPL to groundwater. In addition, the increase of direct transpiration due to the growth of trees and increased saturated zone availability may increase the upward flux of naphthalene toward the upper portion of the saturated zone.

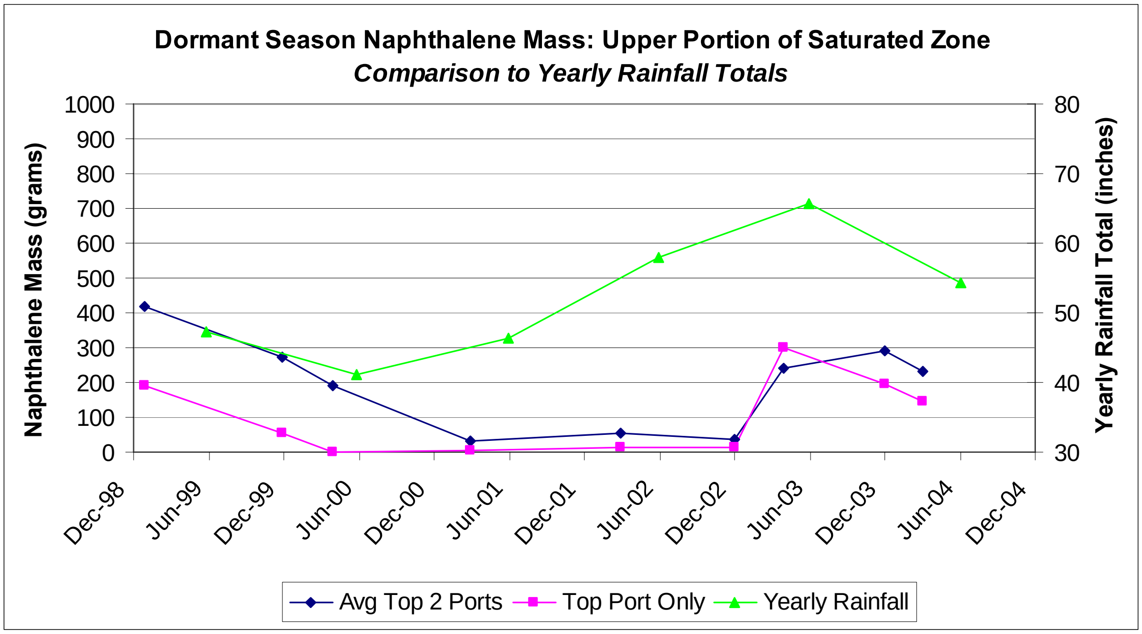


Figure 5.22 Time trend of dormant season naphthalene mass and yearly rainfall.

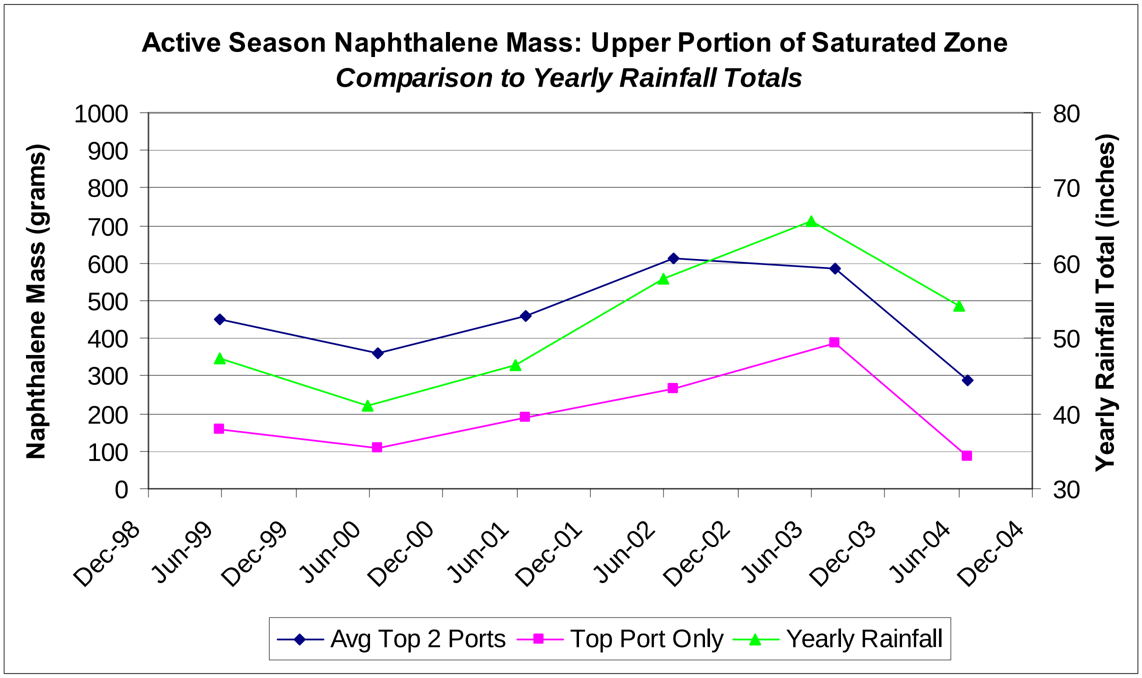


Figure 5.23 Time trend of dormant season naphthalene mass and yearly rainfall.

Since plant uptake is dependent on the amount naphthalene found in the groundwater and the amount of naphthalene found in the upper portion of the saturated thickness is presumably dependent on the magnitude of the saturated thickness, then it was logical to correlate the two. However, since the saturated thickness at the time of the measurement of naphthalene concentrations was not precisely indicative of the trend of the saturated thickness, it was also logical to correlate the amount of naphthalene found in groundwater to yearly rainfall totals. Figures 5.24 and 5.25 illustrate these correlations, respectively.

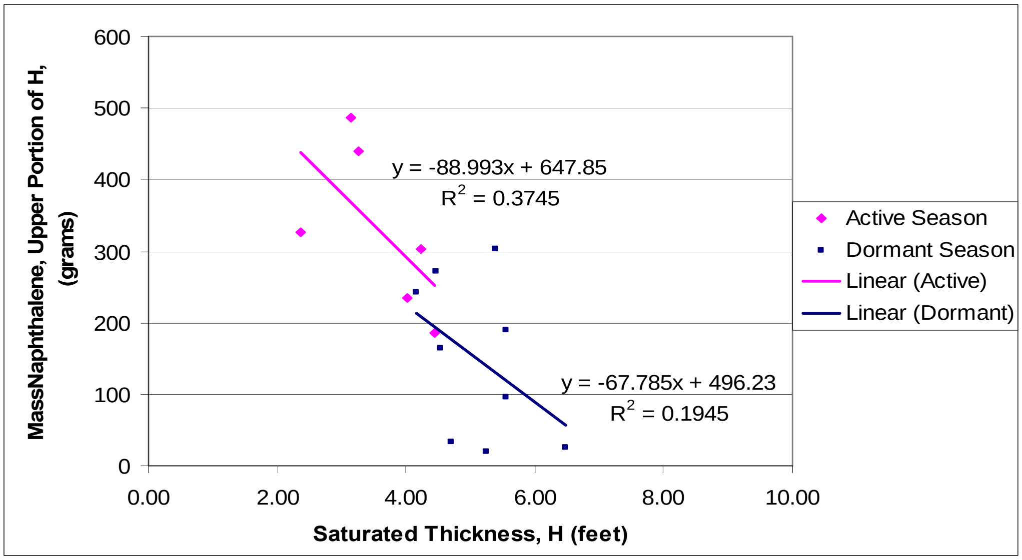


Figure 5.24 Mass of Naphthalene versus saturated thickness, H.

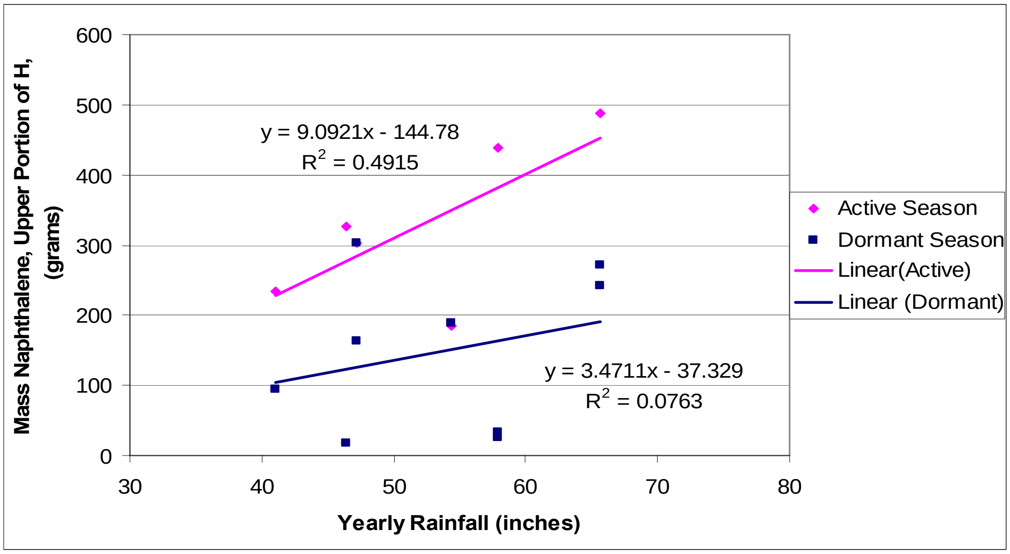


Figure 5.25 Mass of naphthalene versus yearly rainfall totals.

Saturated thickness and yearly rainfall totals appear to correlate better to the mass of naphthalene measured in the upper portion of the saturated zone during the active season. This could be due the upward flux created by the direct transpiration of groundwater by the hybrid poplar trees.

5.4.2 Mass Rate of Plant Uptake of Naphthalene

For 2004, the only concentration data collected during the active season were on July 6th. Since no direct transpiration values were calculated on that day, a *k*-value for volumetric direct transpiration was interpolated from Figure 5.15. This interpolation is illustrated in Figure 5.26.

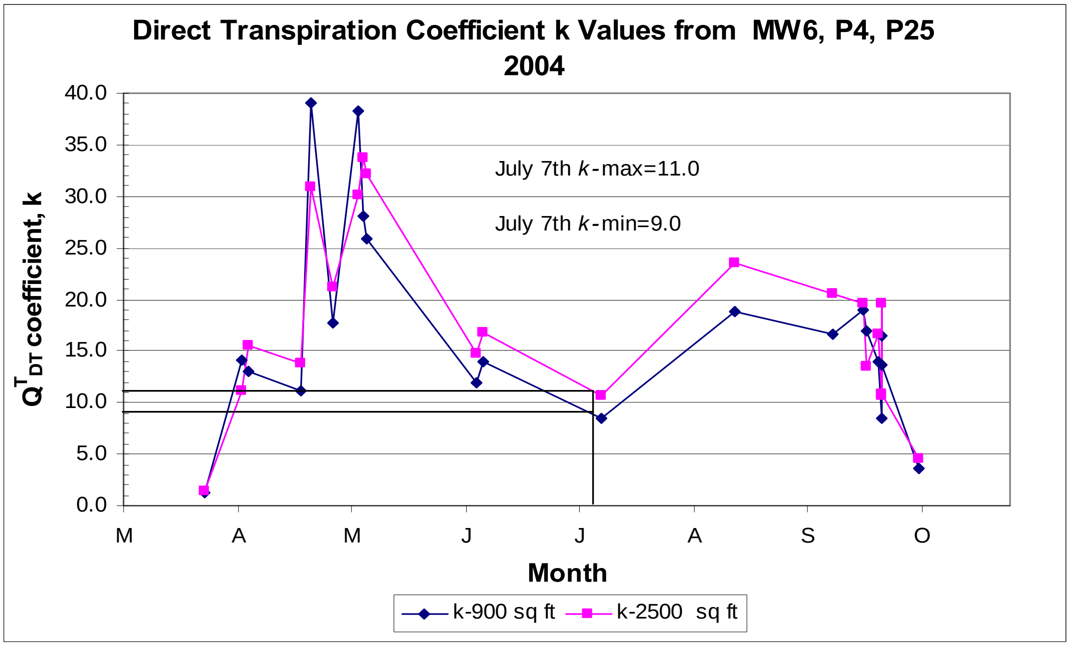


Figure 5.26 Interpolation of k-value for July 6, 2004.

If the average *k*-value from July 6th (k=10) is applied to the equation $Q^T_{DT}=kx^2$ and x is the diameter of every tree within the grid, the mass loss rate of naphthalene from the aquifer may be calculated using equation 5.1. Using a spreadsheet, the mass rate of removal of naphthalene for the Oneida phytoremediation site using the interpolation of concentration data sampled from the average of the top two ports of each multilevel sampler is 493 mg/day. Using data from the top port of each multilevel sampler yields a total mass loss rate of 174 mg/day. These values take into account the concentration of naphthalene found in the uppermost portion of the saturated zone as well as direct volumetric transpiration rates estimated for all trees within the grid for July 6, 2004. This "snapshot" in time provides input into the spatial distribution of both volumetric direct transpiration and naphthalene concentrations in the subsurface.

5.4.3 Estimated Time Trend of Plant Uptake of Naphthalene for Oneida Site

The only season for which naphthalene concentration data exists from the active season is mid-summer. Most data were recorded during early July, though one data set was recorded in June and one in August. To estimate a time trend for plant uptake of naphthalene at the Oneida site, assumptions were made to make up for the lack of measured mid-summer transpiration rates between 1999 and 2003. First, a *k*-value which represents the specific time period during which naphthalene concentrations was measured (mid-summer) was assumed because no direct transpiration rates were calculated specifically for those time periods. Second, in order to make a legitimate comparison, the value of *k* was kept constant from 1999-2004. This assumption is validated by the fact that, on average, mid-summer is generally a dry period at Oneida during which transpiration rates are relatively low.

The average *k*-value interpolated for July 6th is 10. Applying this *k*-value to naphthalene concentrations from 1999-2004 provides a time trend (Figure 5.27) for mass removal of naphthalene by the hybrid poplar trees.

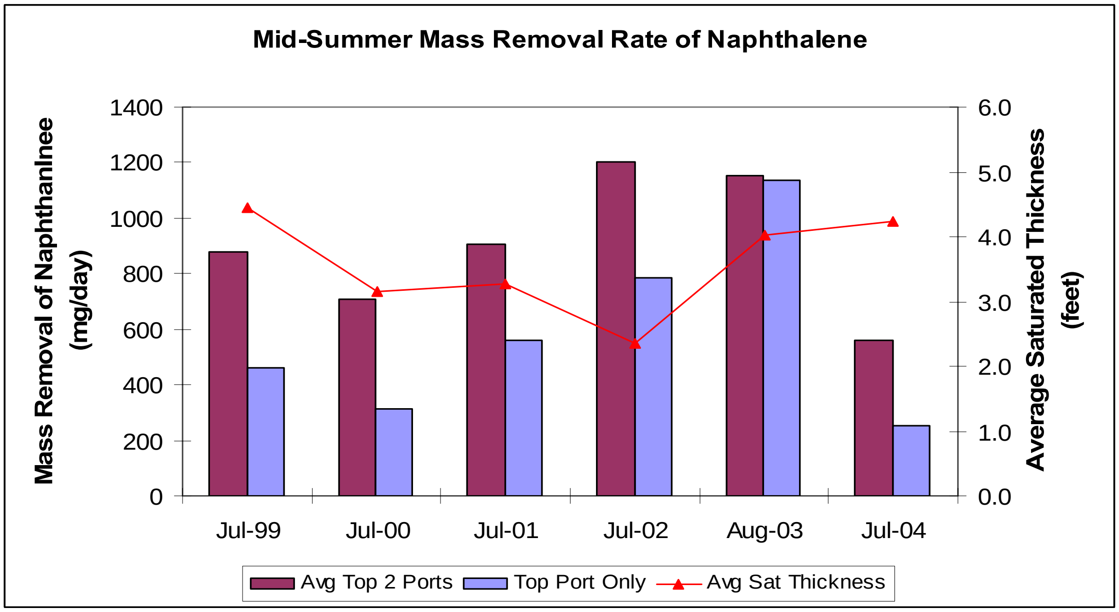


Figure 5.27 Time trend of plant uptake assuming a "typical" mid-summer k-value.

Perhaps the most apparent trend observed in Figure 5.27 is the increase of naphthalene mass removal over time. Keeping the volumetric direct transpiration rate constant illustrates that rate of removal is dependent on the naphthalene concentration found in the uppermost portion of the saturated thickness. As previously mentioned, the concentration of naphthalene found in the uppermost portion of the saturated thickness could be due to increased water table fluctuations caused by increased recharge events and/or by an upward flux of naphthalene caused by the increased direct transpiration of water from the saturated zone.

5.5 Plans and Profiles of Water Table Elevation Data

Using AutoCAD, plans and profiles of water table elevation data calculated using discrete water level measurements were plotted so that the water table elevation and saturated thickness could be compared on a month-to-month basis. The purpose of these plots was to observe the time trend of the entire water table surface beneath the phytoremediation system.

5.5.1 Cone of Depression

At other phytoremediation sites such as the one at Aberdeen, Maryland, a cone of depression has been observed when examining groundwater contours during the active season. At the Oneida site, a cone of depression was not apparent. One reason is due to the number and placement of the piezometers which are used to measure the elevation of the water table. All of the piezometers associated with the phytoremediation system are relatively close to or within the system of trees. In order to observe a cone of depression, the water table would have to be mapped well beyond the boundary of the phytoremediation system. The inability to determine a cone of depression is illustrated by contours for July 6th in Figure 5.28.

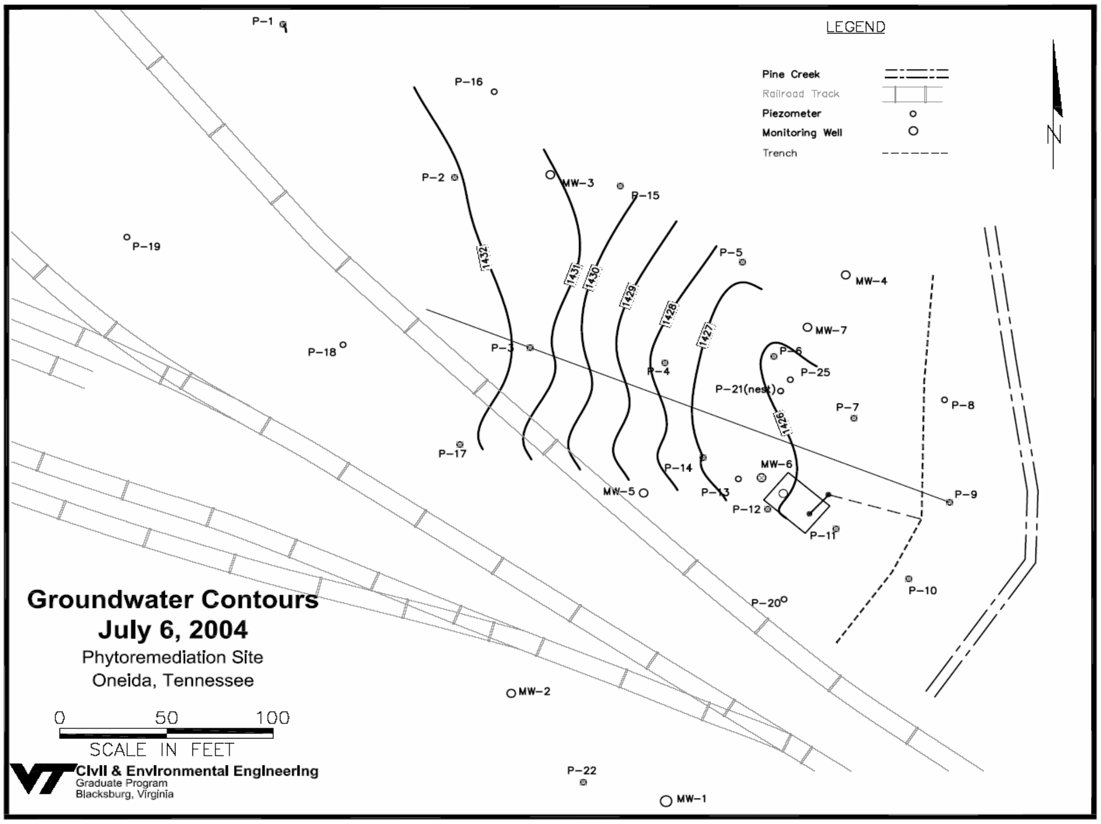


Figure 5.28 Plan view of water table contours for data measured on July 6, 2004.

5.5.2 Change of Hydraulic Profile over Time

In order to better determine the hydraulic nature of the aquifer underlying the phytoremediation system, monthly profiles of the water table are compared. Earlier in this study, it was observed from Figure 5.3 that groundwater fluctuations due to rain events at P3 had a greater magnitude because there were hardly any trees surrounding that location, thus there was less direct transpiration occurring in that area. Figures 5.29-5.31 illustrate comparisons of the water table profile between different months during 2004. It should be noted that the left-hand side of the water table profiles begins northwest of P3 in an area with no trees. The profile enters the treed area at station 00+75 and continues underneath the trees until intersecting P9.

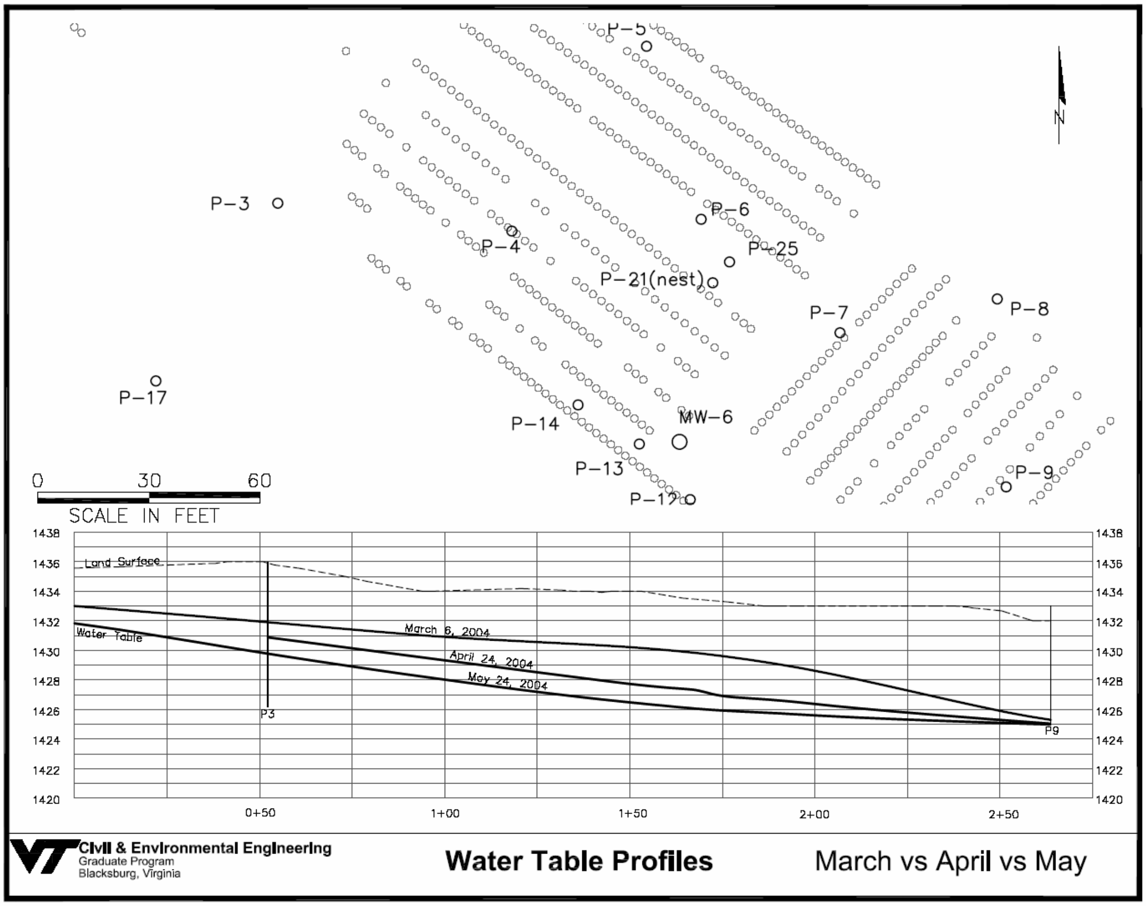


Figure 5.29 Comparison of water table profiles for March, April, and May.

In Figure 5.29 the profile from March is the only observed profile from the dormant season. The profile exhibits an entirely different character than the profiles observed during the active season. During the active season, there is an obvious dip beneath the area of the phytoremediation system which contains trees. This dip is observed throughout the entire course of the active season (April through September).

In the final comparison between September and October (Figure 5.31), the October profile is observed to be slightly higher than that observed for September. It should be noted that September 2004 exhibited twice as much rainfall than October 2004, 7.58 inches versus 3.56 inches, respectively, but also had significantly higher direct transpiration rates. The higher level of the groundwater table in October, the month which received significantly less rain, suggests that the area beneath the trees is influenced by the hybrid poplars more than the area just outside the area beneath the trees. This is due to the fact that in October, the trees were hardly transpiring due to lack of foliage.

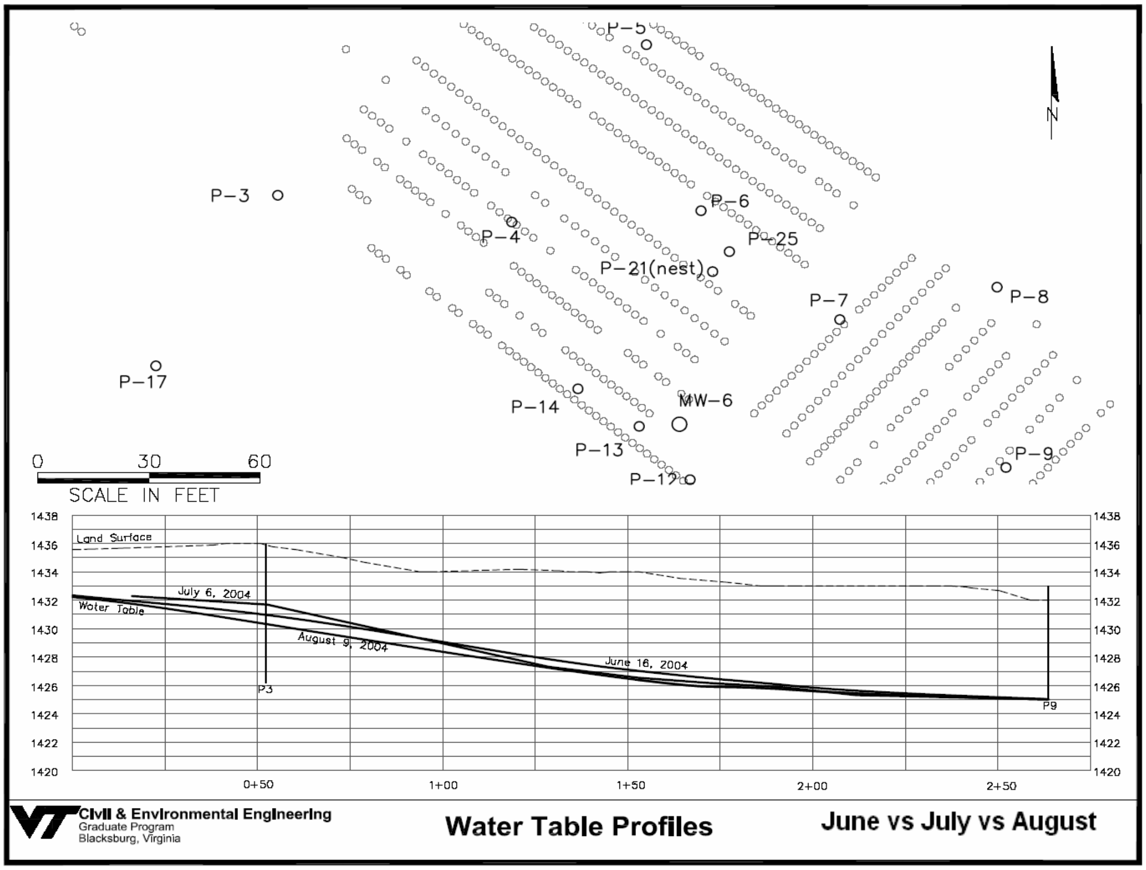


Figure 5.30 Comparison of water table profiles for June, July, and August.

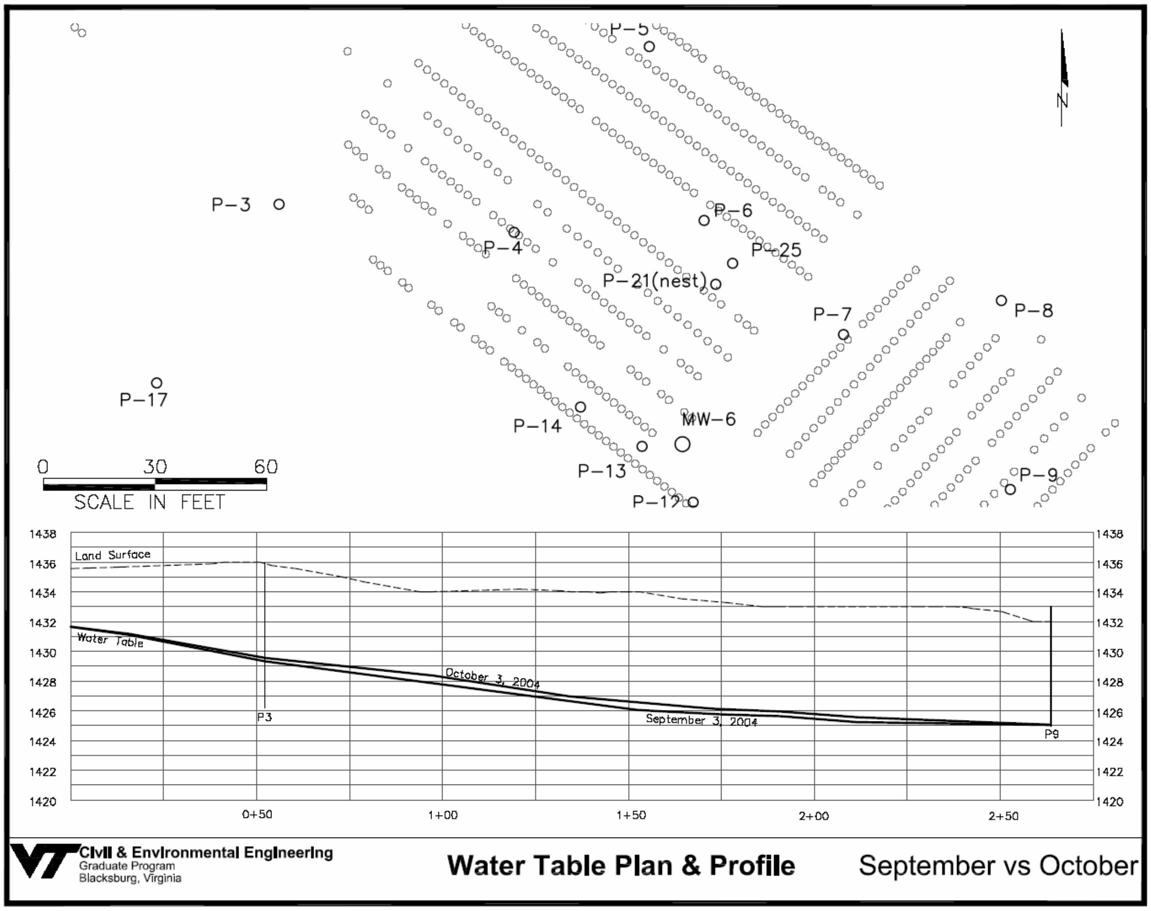


Figure 5.31 Water table profiles for September and October.

6 SUMMARY AND CONCLUSIONS

Several studies have been conducted by Virginia Tech to evaluate the various contaminant attenuation mechanisms of the Oneida phytoremediation system. One mechanism, plant uptake, refers to the “root sorption, uptake, translocation, metabolic transformation, and/or phytovolatilization” of organic chemicals from groundwater (Schnoor, 2002). Plant uptake is a process known to remove contaminant mass from the subsurface. Two significant components of plant uptake are direct transpiration of groundwater and the aqueous concentration of contaminants in groundwater (Vose et al, 2003). Assessment of the seasonal and spatial variability of these components provides an understanding of the plant uptake process which in turn can be used to more thoroughly evaluate the effectiveness of the phytoremediation system.

The primary objectives of this research were: 1) to determine direct transpiration rates (T_{DT}) at the phytoremediation study site, 2) to estimate per tree volumetric direct transpiration rates (Q^{T}_{DT}), and 3) apply per tree volumetric direct transpiration rates to concentration data to quantify the mass removal rate of naphthalene. Direct transpiration rates were calculated for the 2004 growing season by analyzing water table recessions and were validated by comparison to values of evapotranspiration and transpiration calculated during previous site studies between 1999 and 2002 (Panhorst, 2000, Corack, 2003). Utilizing direct transpiration rates, per tree volumetric direct transpiration rates were estimated under the assumption that variability in transpiration rates between trees is directly correlated to tree diameter (Calder, 1993, Vose et al, 2003). Determination of plant uptake rates of naphthalene was accomplished by applying per tree volumetric direct transpiration rates and naphthalene concentration data to the equation for plant uptake of organic chemicals by hybrid poplars (Briggs et al, 1983, Burken and Schnoor, 1998).

6.1 Summary of Findings

6.1.1 Quantification of Direct Transpiration Rates

Direct transpiration rates were quantified from three observation points within the phytoremediation system at various times during the 2004 growing season. In all, 22 values of direct transpiration were calculated between March and October 2004. The daily maximum and mean values for direct transpiration at the study site were 0.0100 and 0.0048 feet/day, respectively. Direct transpiration rates determined for the Oneida phytoremediation site were in good agreement with transpiration rates determined at other sites which utilized hydrologic, groundwater, and sap flow analysis (Meiresonne et al, 1999, Schneider et al, 2002, Vose et al, 2003). Direct transpiration rates increased between early spring and mid-spring in conjunction with an increase in tree foliation. As shown by continuous groundwater level monitoring and water table profiles, the saturated thickness, which was relatively high prior to the active season, decreased with the arrival of spring and remained relatively low and steady throughout the active season. The relatively and consistently low water table throughout the active season was attributed to direct transpiration as well as interception resulting from transpiration of recharge water in the vadose zone. Direct transpiration decreased during early summer. Though assumed to be the peak of the growing season, an unexpected decrease in direct transpiration was observed during early and mid-summer. This decrease was attributed to below average rainfall observed in June which resulted in a relatively long period of decline of the water table. Studies indicate that poplar trees may experience stress as a result of water table decline (Mahoney, 1991). Symptoms of tree stress include a loss of leaves and decreased transpiration rates, both of which were observed during mid-summer. Direct transpiration rates and saturated thickness increased during August and September in conjunction with rainfall events which occurred during that time period. By early October nearly all of the leaves had fallen from the trees, the magnitude of the saturated thickness had begun to increase, and direct transpiration rates had declined considerably.

6.1.2 Estimation of Volumetric Transpiration

Per tree volumetric transpiration rates were estimated by multiplying observed direct transpiration rates by representative areas around each observation point and distributing that quantity amongst the trees found within the representative areas. Plotting per tree volumetric direct transpiration (gallons/day-tree) versus tree diameter (feet) yielded the power equation $Q^{T}_{DT}=kx^{2}$ where k was the volumetric direct transpiration coefficient (gal-ft/ft3) and x was the tree diameter. Since the number of trees within representative areas surrounding each observation point was determined to correspond with phytoremediation system as a whole, values of *k* were applied to all trees found on-site and summed to calculate total volumetric direct transpiration for the phytoremediation system. The peak and average volumetric direct transpiration rates during 2004 were 1750 and 750 gallons/day, respectively. These volumetric direct transpiration rates were in good agreement with evapotranspiration and transpiration rates quantified during previous Oneida phytoremediation site studies (Panhorst, 2000; Corack, 2003).

Estimation of per tree volumetric direct transpiration was based on the assumption that variation in these rates is due to variation of the square of the tree diameter. Trees which were all planted over the course of 1997 ranged from 0.03 to 0.64 feet in diameter. This relatively large variation in diameter of trees which were approximately the same age accounted for the variability of per tree direct transpiration rates. The maximum and average tree diameter observed in 2004 was 0.64 and 0.25 feet, respectively. The daily maximum and mean volumetric direct transpiration rate for average sized trees was 2.48 and 1.05 gallons/day, respectively. The daily maximum and mean volumetric transpiration rate for the maximum sized trees was 15.81 and 6.69 gallons/day, respectively. Direct transpiration rates were in good agreement with transpiration rates of the Aberdeen, Maryland phytoremediation site which were reported to range from 1.4 to 10.8 gallons/day-tree over the course of the season (Schneider et al, 2003). Per tree estimates of volumetric direct transpiration calculated for the Oneida site were also in good agreement with sap flow rates measured at other phytoremediation sites located in Texas, Colorado, and Florida (Vose et al, 2003).

Hinckley reported that 4-year old poplar trees transpire between 5.3 and 6.9 gallon/day based on sap flow measurements (1994). In January 2001, when the trees at the Oneida study site were roughly 4 years old, the maximum tree diameter was 0.41 ft. From direct transpiration rates calculated during 2004, the average and maximum daily volumetric transpiration rate for a tree of this size was 2.79 and 6.59 gallons/day. Considering Hinckley measured sap flow, the amount water transpired from both the vadose zone and the saturated zone, values calculated in this study appear to agree favorably.

6.1.3 Quantification of Naphthalene Removal via Direct Transpiration

The mass removal rate of naphthalene from the aquifer underlying the Oneida phytoremediation site was calculated by applying per tree volumetric direct transpiration rates to local naphthalene concentrations sampled July 6, 2004. The mass removal of naphthalene calculated for the entire plume area ranged from 174 to 493 mg/day on the specified date. If the mass of naphthalene found in the upper portion of the aquifer represents the amount of naphthalene found in the aqueous plume, then the amount of naphthalene removed on July 6, 2004 constitutes from 0.06 to 0.17 percent of the aqueous plume mass. When the per tree volumetric transpiration rates estimated for July 6, 2004 were applied to mid-summer naphthalene concentrations from previous years, the time trend indicated that mass removal rate of naphthalene was generally increasing over time. This increase was in conjunction with an increase in yearly rainfall totals.

Due to dependence on groundwater concentration, mass removal rates of naphthalene vary over the course of the active season due to variation of direct transpiration rates and concentrations of naphthalene in the upper portion of the saturated thickness. Though the concentration of naphthalene found in the upper portion of the saturated zone varies with the magnitude of the saturated thickness, it is expected that other variables such as direct transpiration also influence the variability of naphthalene concentrations.

6.2 Conclusions

Transpiration, a significant component of plant uptake at phytoremediation systems, refers to water removed from the subsurface (vadose zone and saturated zone) through live plants, while the term direct transpiration refers to water specifically from the saturated zone. This study indicates the Groundwater Recession Comparison method may be used to quantify the rate of direct transpiration from the saturated zone of a shallow, unconfined aquifer which underlies a developed stand of phreatophytes. White’s Equation may be utilized for the same purpose since evaporation may be ruled a minor component of evapotranspiration when the canopy of the tree stand is full and the depth to water from the land surface exceeds two feet (White, 1932, Freeze and Cherry, 1979, Vose and Swank, 1992). As opposed to evapotranspiration or total transpiration from both the vadose zone and the saturated zone, direct transpiration from the saturated zone plays an important role when evaluating the effectiveness of a DNAPL-contaminated phytoremediation system since the trees “must transpire enough water from the groundwater layer containing the pollutant to control the transport or decrease the mass of the contaminant” (Vose et al, 2003). The results of this study showed that direct transpiration rates varied considerably over the course of the growing season in response to changes in climatic parameters, leaf area, and depth to water.

To quantify the mass removal rate of aqueous naphthalene, the spatial variability of direct transpiration rates must be carefully considered. Variation in per tree direct transpiration rates was attributed to differences in tree diameter (Vose et al, 2003). Direct transpiration rates were distributed amongst trees within representative areas based on the square of the diameter at breast height and extrapolated to the entire stand of hybrid poplars (Calder, 1993). Accounting for variations in tree diameter proved to be significant due to the wide range of tree diameters found within the phytoremediation system.

Spatial variation in the concentration of contaminants in groundwater was also considered. Naphthalene concentrations in the upper portion of the saturated zone varied over time space due to changes in the magnitude of the saturated thickness. By superimposing per tree volumetric direct transpiration rates over the aqueous naphthalene plume and applying the equation for plant uptake for hybrid poplars by Burken and Schnoor, the mass removal of naphthalene from the aquifer was calculated. The single day mass removal estimate constituted approximately 0.12 % of the aqueous plume mass. If the volumetric direct transpiration rate and the concentration of naphthalene remained constant over time, the time to complete attenuation of naphthalene by plant uptake would be approximately 833 days. Since plant uptake only occurs during the growing season (generally considered 150 days), this would equate to roughly 5.5 years.

The effectiveness of plant uptake is limited by the relationship of direct transpiration and naphthalene concentrations to the magnitude of the saturated thickness.

When the saturated thickness is great enough for direct transpiration to be maximized, the concentration of naphthalene found in the uppermost portion of the saturated zone is usually relatively low. Conversely, when the saturated thickness is in a state of decline and the naphthalene concentrations are relatively high, direct transpiration is generally minimized. This inversely proportional relationship suggests the efficiency plant uptake of is not ideal at the phytoremediation site.

6.3 Future Considerations

In order to help substantiate per tree volumetric direct transpiration rates estimated for the Oneida study site, sap flow analysis should be performed on some of the hybrid poplars. Ideally, sap flow analysis would occur on trees found within a specific representative area surrounding one of the piezometers used for direct transpiration rate calculation. It would be interesting to observe how sap flow correlates to direct transpiration and compare those results with the time trend of direct transpiration rates, saturated thickness, and recharge events.

In order to predict the time to attenuation for naphthalene contamination, GMS should be used to estimate the entire mass of naphthalene found within the saturated thickness. Only by observing the decrease in mass found in the entire saturated thickness can a determination be made regarding the effectiveness of the phytoremediation system with regard to attenuation of contaminants.

Consideration should be given to the spacing of the hybrid poplar trees at the Oneida phytoremediation site. If the trees were thinned, many more trees would be able to grow to their maximum potential. The resulting increased root depth would allow more direct transpiration of groundwater containing higher concentrations of naphthalene. This would effectively increase the rate at which naphthalene mass is being removed.

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