Rate of Contamination Removal of Two Phytoremediation Sites at the DOE Portsmouth Gaseous Diffusion Plant

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ABSTRACT

This paper describes applications of phytoremediation at the Portsmouth Gaseous Diffusion Plant (PORTS), a Department of Energy (DOE) Facility that enriched uranium from the early 1950s until 2000. Phytoremediation has been implemented to assist in the removal of TCE (trichloroethylene) in the groundwater at two locations at the PORTS facility: the X-740 area and the X-749/X-120 area.

Phytoremediation technology is based on the ability of certain plants species (in this case hybrid poplar trees) and their associated rhizospheric microorganisms to remove, degrade, or contain chemical contaminants located in the soil, sediment, surface water, groundwater, and possibly even the atmosphere. Phytoremediation technology is a promising clean-up solution for a wide variety of pollutants and sites.

Mature trees, such as the hybrid poplar, can consume up to 3,000 gallons of groundwater per acre per day. Organic compounds are captured in the trees' root systems. These organic compounds are degraded by ultraviolet light as they are transpired along with the water vapor through the leaves of the trees.

The phytoremediation system at the X-740 area encompasses 766 one-year old hybrid poplar trees (*Populus nigra x nigra*, *Populus nigra x maximowiczii*, and *Populus deltoides x nigra*) that were planted 10 feet apart in rows 10 feet to 20 feet apart, over an area of 2.6 acres. The system was installed to manage the VOC contaminant plume. At the X749/X-120 area, a phytoremediation system of 2,640 hybrid poplar trees *(Populus nigra x maximowiczii*) was planted in seven areas/zones to manage the VOC contaminant plume. The objectives of these systems are to remove contamination from the groundwater and to prevent further migration of contaminants. The goal of these remediation procedures is to achieve completely mature and functional phytoremediation systems within two years of the initial planting of the hybrid poplar trees at each planting location.

There is a direct relationship between plant transpiration, soil moisture, and groundwater flow in a phytoremediation system. The existing monitoring program was expanded in 2004 in order to evaluate the interactions among these processes. The purpose of this monitoring program was to determine the rate of contaminant removal and to more accurately predict the amount of time needed to remediate the contaminated groundwater. Initial planting occurred in 1999 at the X-740 area, with additional replanting in 2001 and 2002. In 2003, coring of selected trees and chemical analyses illustrated the presence of TCE; however, little impact was observed in groundwater levels, analytical monitoring, and periodic tree diameter monitoring at the X-740 area.

To provide better understanding of how these phytoremediation systems work, a portable weather station was installed at the X-740 area to provide data for estimating transpiration and two different systems for measuring sap flow and sap velocity were outfitted to numerous trees. After evaluating and refining the groundwater flow and contaminant transport models, the data gathered by these two inventive methods can be used to establish a rate of contaminant removal and to better predict the time required in order to meet remediation goals for the phytoremediation systems located at the PORTS site.

INTRODUCTION

The Portsmouth Gaseous Diffusion Plant (PORTS), a Department of Energy (DOE) Facility, enriched uranium from the early 1950s until 2000. Phytoremediation has been implemented to assist in the removal of TCE (trichloroethylene) in the groundwater at two locations at the PORTS facility: the X-740 area and the X-749/X-120 area.

The X-740 Waste Oil Handling Facility was in operation from 1982 to 1992. This facility was primarily used for staging drums of non-radionuclide-contaminated waste oils and solvents generated by various activities at the plant. In 1993 the X-740 facility underwent closure in compliance with the Resource Conservation of Recovery Act (RCRA). Groundwater contamination remaining at the facility has detectable levels of TCE.

The X-120 Goodyear Training Facility has been in operation since plant construction as a machine shop, paint shop, and warehouse space. The X-120 facilities were demolished and removed in the late 1970s, prior to the more recent construction of the Gas Centrifuge Enrichment Plant. Several remedial investigations, however, have identified various VOCs (volatile organic compounds), primarily TCE, at detectable levels in the groundwater.

Located approximately 500 feet to the southeast of the X-120 Goodyear Training Facility is the X-749 Landfill. The X-749 Landfill comprises northern and southern segments. The northern segment was utilized from 1955 to 1989; it is approximately 7.5 acres in size. The southern segment was utilized from 1986 to 1989; it is approximately 4 acres in size. The X-749 Landfill is currently treated as a single unit due to the groundwater plume which lies under both segments of the landfill. In 1989, the 11.5-acre landfill underwent closure in compliance with the Resource Conservation and Recovery Act (RCRA). The closure activity included the installation of slurry walls along the north and west sides of the landfill and the installation of groundwater trenches along the east and southwest sides of the landfill. These installed features serve as source control for groundwater contamination. In addition, a multi-layered landfill cap was installed over the complete facility. It is believed that the X-749 Landfill is a continuing source of contamination to the groundwater. Currently at the X-749/X-120 area the TCE levels in the groundwater are above the targeted risk level of 1×10^{-6}.

Phytoremediation technology is based on the ability of certain plants species (in this case hybrid poplar trees) and their associated rhizospheric microorganisms to remove, degrade, or contain chemical contaminants located in the soil, sediment, surface water, groundwater, and possibly even the atmosphere. Phytoremediation technology is a promising clean-up solution for a wide variety of pollutants and sites. Some of the benefits of phytoremediation technology are:

- It is a passive technology, producing minimal or no waste during tree installation or during remediation.
- It is 10% to 20% less costly than mechanical treatments in terms of overall operating costs.
- It is an *in situ* (in place) technology that produces an aesthetically pleasing environment.
- It is entirely solar-driven.
- Treated soil remains in place and is reusable following treatment.
- It is applicable to non-source areas and slow moving plumes.

Mature trees, such as the hybrid poplar, can consume up to 3,000 gallons of groundwater per acre per day. Organic compounds are captured in the trees’ root systems. These organic compounds are degraded by ultraviolet light as they are transpired along with the water vapor through the leaves of the trees.

The phytoremediation system at the X-740 area encompasses 766 one-year old hybrid poplar trees (*Populus nigra x nigra*, *Populus nigra x maximowiczii*, and *Populus deltoides x nigra*) that were installed via two innovative planting methods, the trench/boring design and the borehole design. The system was installed to manage the VOC contaminant plume. At the X749/X-120 area, a phytoremediation system of 2,640 hybrid poplar trees *(Populus nigra x maximowiczii*) was planted in seven areas/zones to manage the VOC contaminant plume. The objectives of these systems are to remove contamination from the groundwater and to prevent further migration of contaminants. The goal of these remediation procedures is to achieve completely mature and functional phytoremediation systems within two years of the initial planting of the hybrid poplar trees at each planting location.

There is a direct relationship between plant transpiration, soil moisture, and groundwater flow in a phytoremediation system. The existing monitoring program was expanded in 2004 in order to evaluate the interactions among these processes. The purposes of this monitoring program were to establish a rate of contaminant removal and a means to better predict the amount of time needed to remediate the contaminated groundwater. Initial planting occurred in 1999 at the X-740 area, with additional replanting in 2001 and 2002. In 2003, coring of selected trees and chemical analyses illustrated the presence of TCE: however little impact was observed in groundwater levels, analytical monitoring, and periodic tree diameter monitoring at the X-740 area.

To provide better understanding of how these phytoremediation systems worked, a portable weather station was installed at the X-740 area to provide data for estimating transpiration and two different systems for measuring sap flow and sap velocity were outfitted to numerous trees. One system uses energy balance sensors, which measure the rate of heat convection by sap flow. A collar which is non-intrusive surrounds the tree branch, transmitting a real-time measurement of sap flow. The second system uses a two-probe set that measures thermal dissipation by comparing a heated probe to a reference probe. Tree branches and tree trunks contained sensors for two weeks, after which the sensors were moved to other locations.

Sap flow measurement serves as a means of estimating the transpiration of instrumented trees. During the monitoring period, meteorological information was gathered while sap flow data were analyzed according to tree diameter. Based on the tree diameter, a transpiration rate that is proportional to monitored sap flow is assigned to the trees in question. Weather data and groundwater data in conjunction with soil moisture data from various depths are used to allocate transpiration to either precipitation or (trench) groundwater. After evaluating and refining the groundwater flow and contaminant transport models, the data gathered by these two inventive methods can be used to establish a rate of contaminant removal and to better predict the time required in order to meet remediation goals for the phytoremediation systems located at the PORTS site.

X-740 AREA HISTORY

The X-740 Phytoremediation Area is located west of the former X-740 Waste Oil Handling Facility and south of the X-530A Switchyard, as shown in Fig. 1. The trees were planted in an area that had previously been used as a switchyard during construction of the PORTS facility.

In 1999, the Ohio EPA selected the use of *in situ* treatment for the X-740 groundwater plume remediation. Phytoremediation was chosen as the best remedial option for treatment of the groundwater in the X-740 area. The natural growth process of biological systems is utilized by phytoremediation technology to attenuate and reduce contamination in groundwater.

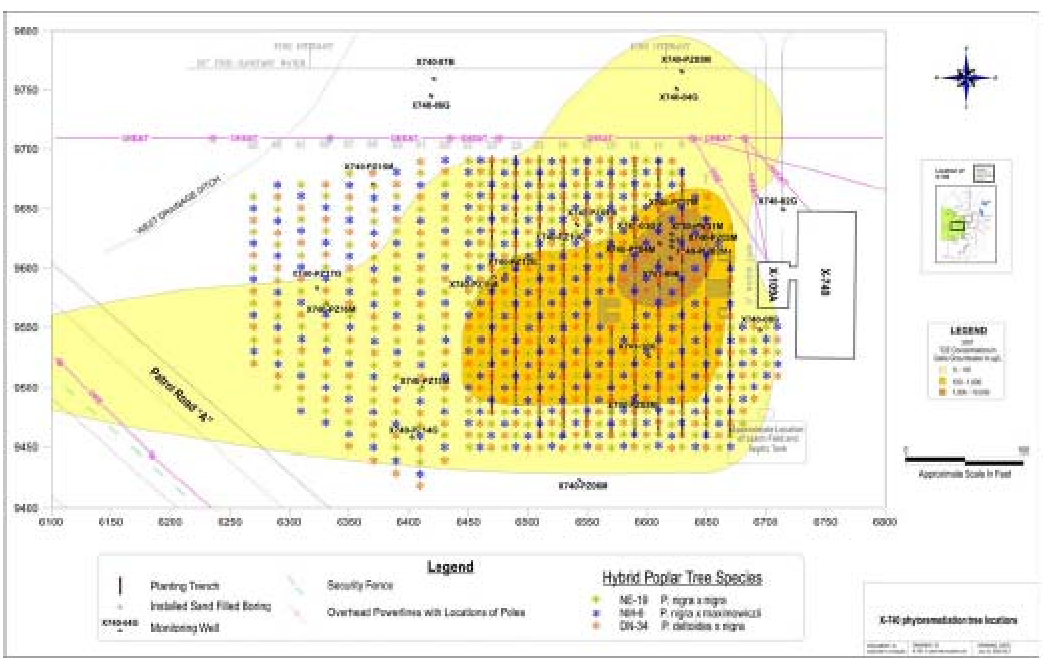

Fig. 1. Overview of the X-740 Phytoremediation Area, TCE Plume Extent, and Tree Planting Locations

In order to provide greater resistance to various plant diseases and resilience, three hybrid poplar tree species were selected. A multi-species approach increases the likelihood of success for the phytoremediation area. The three hybrid poplar tree species were selected for the application because of their high growth rate and yield, high evapotranspiration rates, root zone depth, long life span, and ease of growth. The 766 one-year old hybrid poplar trees comprising the X-740 phytoremediation system were planted 10 feet apart in rows 10 feet to 20 feet apart, over an area of 2.6 acres, in order to manage the volatile organic compound (VOC) contaminant plume. The objectives of this task were to remove contamination from the groundwater and to prevent migration of contaminants from the area. The goal of the remediation procedure was to achieve a completely mature and functional phytoremediation system within 2 to 3 years of the initial planting of the hybrid poplar trees. The organic compounds were then to be captured and removed from the groundwater. It is estimated that the cleanup standards can be achieved within 10.5 years after the trees reach maturity.

X-749 AREA HISTORY

The X-749 Phytoremediation Area is located approximately 500 feet to the southeast of the X-120 Goodyear Training Facility is the X-749 Landfill as shown in Figure 2. The X-749 Landfill comprises northern and southern segments. Currently, the X-749 Landfill is treated as a single unit due to the groundwater plume which lies under both segments of the landfill. In 1989, the 11.5-acre landfill underwent closure in compliance with the Resource Conservation and Recovery Act (RCRA). The closure activity included the installation of slurry walls along the north and west sides of the landfill and the installation of groundwater trenches along the east and southwest sides of the landfill. These installed features serve as source control for groundwater contamination. In addition, a multi-layered landfill cap was installed over the complete facility. The captured contaminated groundwater is treated at an on-site groundwater treatment facility.

In 2001, the Ohio EPA selected the use of *in situ* treatment for the X-749 groundwater plume remediation. Phytoremediation was chosen as the best remedial option for treatment of the groundwater in the X-749 area. The natural growth process of biological systems is utilized by phytoremediation technology to attenuate and reduce contamination in groundwater.

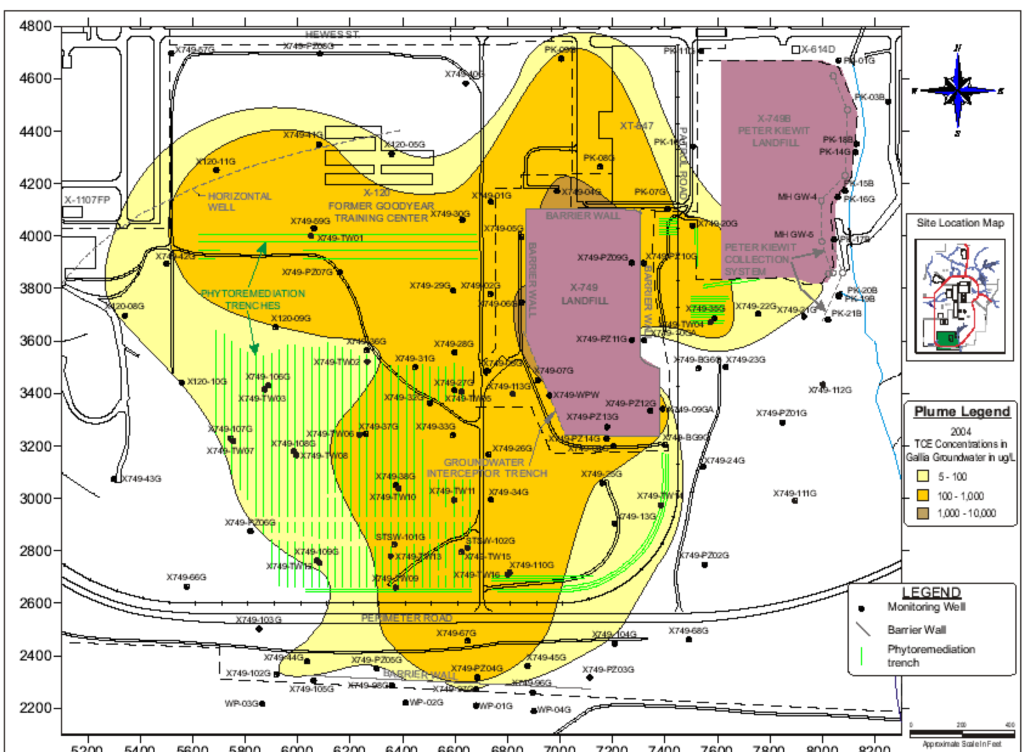

Fig. 2 X-749/X-120/Peter Kiewit Landfill Area

Fig. 2. Overview of the X-749 Phytoremediation Area, TCE Plume Extent, and Tree Planting Locations

The species of hybrid poplar trees that was chosen for the X-749/X-120 phytoremediation project is a cross between the European black poplar and an Asian balsam poplar. The species is *NM-6, Populus nigra x Populus maximowiczii*. This species of hybrid poplar, developed in the 1970s, grows vigorously even into late autumn.

This hybrid poplar tree species was selected for the application because of its high growth rate and yield, high evapotranspiration rates, root zone depth, long life span, and ease of growth. Additionally, this species can grow in excess of 60 feet in length and is more likely than most other species to grow in harsher soil conditions. The 2,640 one-year old hybrid poplar trees of the X-749 phytoremediation system were planted in rows typically 10-30 feet apart, with 10 feet between each row of trees over an area of 41 acres, in order to manage the volatile organic compound (VOC) contaminant plume. The rows were planted perpendicular to the direction of groundwater flow. A sand stack and trenching/boring design was implemented throughout the 41 acres of the X-749/X-120 area.

The objectives of this task were to remove contamination from the groundwater and to prevent migration of contaminants from the area. The goal of the remediation procedure was to achieve a completely mature and functional phytoremediation system within 2 to 3 years of the initial planting of the hybrid poplar trees. The organic compounds were then to be captured and removed from the groundwater. It is estimated that the cleanup standards can be achieved within 10.5 years after the trees reach maturity.

DESIGN/METHODS/RESULTS

The existing monitoring program at the PORTS site was expanded in 2004 in order to evaluate the interactions among plant transpiration, soil moisture, and groundwater flow processes. The purposes of this monitoring program were to determine the rate of contaminant removal and to more accurately predict the amount of time needed to remediate the contaminated groundwater.

Two methods were utilized to accurately measure sap flow. The initial method used energy balance sensors, which measure the rate of heat convection by sap flow. By measuring sap flow and sap velocity of numerous trees, this method measures the water consumption of the trees. Along with convective heat flux, the rate of water flux along the stem was calculated.

The second method utilizes a two-probe set that measures thermal dissipation by comparing a heated probe to a reference probe. The temperature difference and the maximum temperature difference at zero flow provide a direct and calibrated conversion of sap flow. Because sap flow can vary around the circumference of a tree, accurate calculations require that multiple probes must be inserted into a single tree. Sap flow data can be used to make a predictive model of annual water consumption.

The tree coring study was conducted in 2003. Samples were collected from 16 trees in the X-740 Phytoremediation area. Measurable levels of TCE, although relatively low, were detected in three of the 16 core samples. These results indicated that the trees were utilizing some groundwater containing TCE. Along with the tree coring study, tree-stem air diffusion trap sampling was conducted. No TCE was detected in the tree-stem air diffusion samples.

A portable weather station was installed at the X-740 area to provide data for estimating transpiration. The weather station can measure air and ground temperature, wind direction and speed, humidity, barometric pressure, solar radiation, and precipitation. This information can be used to estimate potential evapotranspiration on an hourly basis. Evapotranspiration rates between May 29, 2004 and June 5, 2004 are demonstrated in Figure 3.

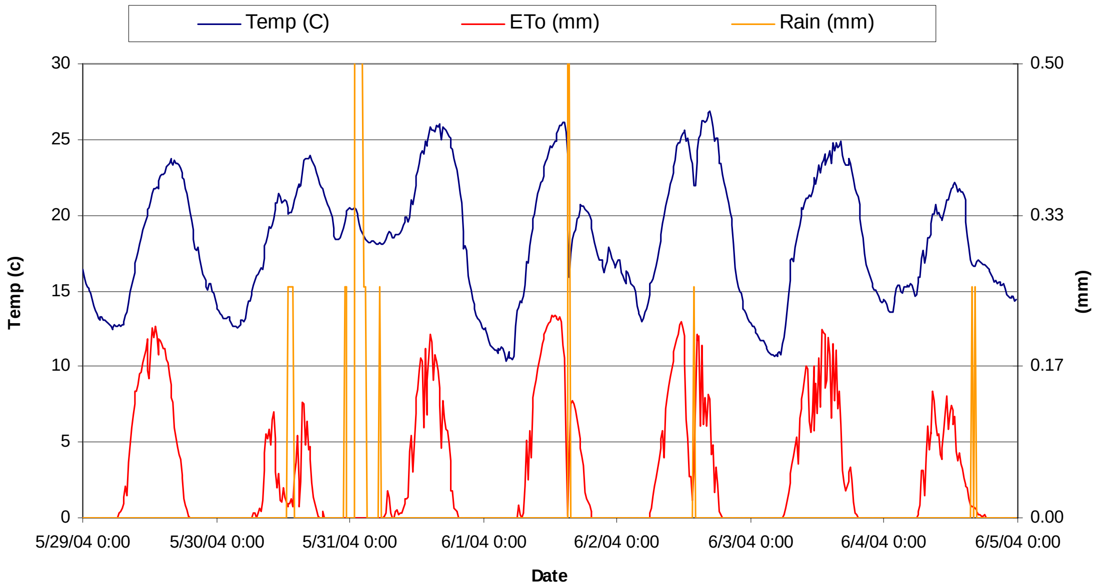

Fig. 3. Demonstration graph of the evapotranspiration rates May 29, 2004 - June 5, 2004

Soil moisture data were collected using a thetaprobe sensor connected to a soil moisture datalogger. The thetaprobe measures volumetric soil water content within 2%. Two soil moisture loggers were installed at the X-749 area in 2004. The soil moisture probes are buried within the area where the trees are planted. Also, background soil moisture data were collected from an undisturbed location near the weather station.

Monthly inspections at the X-740 area were conducted between October and March while the quarterly inspections were conducted between April and September during the growing season. During these inspections, the condition of trees, tree growth rates/patterns, and mortality rates/patterns were examined. In August 2000, maintenance included the replanting of 52 trees and routine activities. In April 2002, maintenance included replanting of 20 trees and continued routine maintenance at the X-740 Phytoremediation area. A total of 240 trees were planted with the trenching approach and 526 were planted with the non-trenched rows approach. The 5-year evaluation noted that the trees planted in the trench are thriving with only 15 recorded as dead and 67.1% having a diameter larger than 8 cm. The non-trench planted trees are also thriving but not as well as the trench planted trees. The 5-year evaluation noted 44 non-trench planted trees recorded as dead and only 4.2% having diameters larger than 8 cm. Overall the trees are surviving within predicted expectations. The existing monitoring program was expanded in 2004 to evaluate the interactions among these processes.

The Integrated Groundwater Monitoring Plan (IGWMP) began in 1999 and was expanded within 5 years. This plan ensures the routine maintenance and monitoring of the PORTS plant and the evaluation and interaction among these processes. Data collected between November 2001 through November 2004 at the four designated monitoring wells (X740-03G, X740-10G, X740-PZ10G, and X740-PZ12G) demonstrated lower TCE concentrations during the growing season than during the dormant season. This variation is due to several factors, including rainfall and the influence of the trees which can not be separated. The TCE concentrations are below the Ohio EPA preliminary performance goal of 495 mg/L in three of the four wells. Well X740-03G is the only well above the target concentration. See Figure 4 for an overview of the four designated monitoring well TCE concentrations versus the EPA preliminary performance goal.

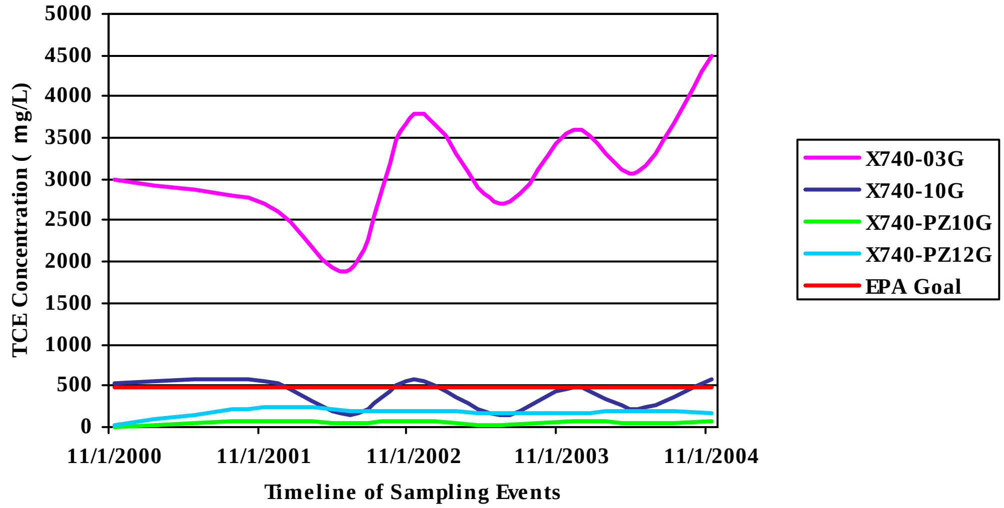

Fig. 4. Overview of TCE concentrations of the four designated X-740 monitoring wells
Note: Three of the designated monitoring wells are below the EPA preliminary performance goal of 495 mg/L

Groundwater level measurements have been collected in the past and are continually collected at the X-740 Phytoremediation area per IGWMP requirements. In the years 2000, 2001, and 2002, there was a detectable change in the groundwater flow in the area through the growing season. Potentiometric surface maps of the area throughout this time illustrate the influence of the phytoremediation system on the groundwater flow. Severe precipitation fluctuations have occurred in the Piketon, Ohio area between 2001 and 2003. The growing season of 2001 was extremely dry, 2002 was normal, and 2003 was extremely wet. The growing season of 2003 demonstrated a downward trend in the groundwater elevations, indicating increased groundwater demand. Groundwater elevations rose during November 2003, the dormant season, demonstrating the effectiveness of the phytoremediation system. The Figure 6 hydrograph demonstrates the X740-03G monitoring well groundwater elevation changes.

There is a direct relationship between plant transpiration, soil moisture, and groundwater flow in a phytoremediation system. These methods were implemented in order to establish a rate of contaminant removal and a means to better predict the amount of time needed to remediate the contaminated groundwater.

Weather data and groundwater data in conjunction with soil moisture data from various depths are used to allocate transpiration to precipitation or (trench) groundwater. After evaluating and refining the groundwater flow and contaminant transport models, the data assembled can be utilized to establish a rate of contaminant removal and to develop an accurate time line for meeting the remediation goals of the phytoremediation systems at the PORTS site.

CONCLUSION

After five years of monitoring, the movement of groundwater in the area of the X-740 Phytoremediation Project was established by the groundwater level measurements conducted monthly during the growing season (summer months) and quarterly during the remaining months. Although the water level measurements demonstrate water removal from the trenches, the sand pipes do not appear to be removing an adequate amount of groundwater to allow significant TCE removal by the trees.

The four designated monitoring wells (X740-03G, X740-10G, X740-PZ10G, and X740-PZ12G) demonstrated lower TCE concentrations during the growing season than during the dormant season. This discrepancy may be due to the influence of the trees affecting the groundwater during the growing season. The TCE concentrations are below the Ohio EPA preliminary performance goal of 495 mg/L in three of the four wells. Well X740-03G is the only well above the target concentration. The trees in the X-740 Phytoremediation area are removing 1,176 gallons/acre/day. The total water consumption during 2004 growing season was 229,000 gallons/acre.

The direct relationship between plant transpiration, soil moisture, and groundwater flow in a phytoremediation system was demonstrated by a combination of many monitoring methods. The weather data and groundwater data in conjunction with soil moisture data from various depths make it possible to allocate transpiration to either precipitation or (trench) groundwater. The sap flow monitoring data quantifies and supports remediation predictions for the X-740 and X-749 areas.

The tree coring study revealed measurable levels of TCE in three of the 16 trees sampled. Because the TCE was detected at relatively low concentrations, however, this discovery proves that the trees are utilizing at least some of the groundwater containing TCE.

This corrective action was installed in 1999, and approximately two years are required for the root system to mature sufficiently to have an observable impact on groundwater. Because it has been 5 years since the X-740 phytoremediation system was installed, only 3 years of effective growing seasons have elapsed for the trees to reduce the TCE concentrations in the area. Although the TCE concentrations do not consistently reach the Ohio EPA preliminary performance goal of 495 mg/L in all four designated monitoring wells, it is evident that the trees at the X-740 Phytoremediation area are impacting the groundwater in the area.

The corrective action for the X-749 area was completed in 2003, and approximately two years are required for the root system to mature sufficiently to have an observable impact on groundwater. Because it has been 2 years since the X-749 phytoremediation system was installed, no effective growing seasons have elapsed for the trees to reduce the TCE concentrations in the area. The results and knowledge gained from the X-740 area may be used to refine assumptions and approaches at X-749/X-120 area.

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