ANALYSIS OF HYDROLOGIC DATA TO EVALUATE PHYTOREMEDIATION SYSTEM PERFORMANCE

William H. Schneider (schneidw@mail.rfweston.com)
(Roy F. Weston, Inc., Albuquerque, New Mexico)
Steven R. Hirsh (U.S. Environmental Protection Agency (U.S. EPA) Region III, Philadelphia, Pennsylvania)
Harry R. Compton (U.S. EPA, Environmental Response Team, Edison, New Jersey)
Amy E. Burgess and John G. Wrobel (U.S. Army, Aberdeen Proving Ground, Maryland)

ABSTRACT: A long-term environmental monitoring program is providing hydrologic data that demonstrates poplar trees are influencing groundwater flow at the J-Field site, Aberdeen Proving Ground, Maryland. Advanced data collection and analyses techniques have enabled researchers to construct a water budget for the study area and to estimate the amount of groundwater the trees are transpiring on a daily and annual basis. During the growing season, groundwater flow is influenced by the transpiration activities of the poplar trees, as evidenced by shifts in groundwater flow towards the center of the poplar grove and a measurable cone of depression on the water table. Continuous monitoring of the aquifer indicates that the trees transpire enough groundwater to produce daily fluctuations of the shallow water table. Estimates of peak summer groundwater transpiration rates for the poplar grove range from 12 to 21 gallons per day per tree (gal/day^{-1}/tree^{-1}) (45 to 80 L/day^{-1}/tree^{-1}) based on sap flow measurements and later substantiated by meteorological data and groundwater modeling analyses. The poplar trees induce upward gradients towards the tree roots. During the summer, gradient shifts were observed to a maximum depth of 25 ft (7.6 m). Hydrologic analyses demonstrate that the trees are intercepting a significant component of groundwater flow during the summer and early fall and are thereby limiting the discharge of contaminated groundwater to the marsh during this period. Trees tissue and transpiration gas sampling confirm the poplar trees are withdrawing contaminant mass from the aquifer.

These hydrologic and geochemical data demonstrate the J-Field site provides ideal hydrogeologic conditions for the successful application of phytoremediation. J-Field is underlain by a low permeability, shallow water table aquifer that discharges to a biologically active freshwater marsh. Based on the favorable results of the pilot study, 600 additional trees are being planted to improve the capacity of the phytoremediation system to provide hydraulic containment of a contaminant plume.

INTRODUCTION

Phytoremediation is becoming a more commonly accepted technology for remediating contaminated soil and groundwater (U.S. EPA, 2000). At the J-Field site, Aberdeen Proving Ground, Maryland, a pilot-scale phytoremediation study is being conducted to evaluate the effectiveness of hybrid poplar trees (*Populus deltoids x trichocarpa)* to hydraulically contain and potentially remediate a shallow volatile organic compound (VOC) groundwater plume. In 1996, 183 poplar trees were planted in a 0.4-hectare (1-acre) area to intercept the VOC plume as it migrates to a freshwater marsh.

Since 1996, extensive monitoring of the phytoremediation system has been conducted to evaluate the system performance. The monitoring program has evaluated the fate pathways of transpired contaminated groundwater (Burken, 2001 and 2002), rhizosphere degradation processes (Pardue et al., 2000), poplar tree transpiration rates (Haroski et al., 2000), and analysis of poplar tree influences on groundwater hydrology (Schneider et al., 2000). The studies have demonstrated that the poplar trees are effective at providing seasonal hydraulic containment of the VOC plume and capable of reducing VOC mass by biotransforming VOCs within the transpiration stream and potentially enhancing *in situ* biodegradation through rhizosphere processes. A detailed summary of the findings of the studies is presented in Hirsh et al. (2002).

Objectives. A primary remedial goal at J-Field is to use the poplar trees to provide hydraulic control of shallow contaminated groundwater. This paper summarizes the development of a hydrologic monitoring and analysis program designed to evaluate the remedial performance of the phytoremediation system from the hydrologic perspective. This paper provides a case study of the application of hydrologic analysis to support a remedial program. The study objectives include the following: (1) estimate the extent of seasonal hydraulic containment generated by the poplar trees, (2) evaluate the depth of hydraulic influence exerted by the poplar trees, (3) generate a water budget of the groundwater system at J-Field, and (4) utilize a transient groundwater model to evaluate the remedial performance of the phytoremediation system in response to planting 600 additional trees.

MATERIALS AND METHODS

Field Monitoring. The hydrologic monitoring program conducted from spring 2000 to summer 2001. The field sampling program consisted of continuous recordings of fluid pressure in the surficial aquifer that underlies J-Field. Pressure transducers were placed at the midpoint of the well screens and connected to automated data loggers that monitored the changes in fluid pressures from the 21 monitor wells. These data were supplemented by manual water levels collected from 37 additional monitor wells with electronic water level sensors. Details of the monitoring program are presented in an annual J-Field monitoring report (General Physics, 2001).

The U.S. Army collected site-specific weather data at the Phillips Air Field, Aberdeen, Maryland, that was used in the hydrologic analysis. The data include temperature, wind speed, humidity, precipitation, barometric pressure, and solar radiation. Additional data were obtained from the Baltimore-Washington International Airport database. Tidal fluctuation data were collected at a gauging station that monitors the Gunpowder River. Transpiration rates for individual trees were estimated by measuring sap flow using the Dynagage™ Flow 32 system. Sap flow, tree height, diameter-at-breast-height, and on-site weather conditions have been examined seasonally over a five-year period. Two methods were used to assess tree transpiration rates: (1) an energy balance method, and (2) a thermal dissipation probe method. Sap flows and tree growth data were used to calculate current and future transpiration rates as presented by Haroski et al. (2000).

Hydrologic Analysis. The complex hydrology at J-Field requires careful interpretation of the groundwater data to account for confounding factors such as changing barometric pressure, tidal forcing, groundwater recharge, and delayed yield. The characteristics of the J-Field hydrologic system, specifically the low permeability aquifer, subsurface heterogeneities, and the proximity of the site to a freshwater marsh and tidal estuary, make evaluating these factors critical to accurately assess the effects of the plantation on the aquifer. Methods for evaluating the data, which were based on techniques presented by Landmeyer (2001), are discussed in the following paragraphs.

An analysis of groundwater flow was conducted using water table mapping techniques and hydrograph interpretation to evaluate seasonal changes in hydraulic gradients that may be attributed to aquifer responses to transpiration. Prior to plotting the groundwater data, the data first were analyzed to assess the aquifer responses to barometric pressure and tidal forcing. Aquifer efficiency calculations to tides and barometric pressure changes were conducted to assess the need to filter out the physical effects based on methods presented by Kruseman and de Ridder (1991). Where applicable, groundwater data were corrected for these effects and then used to generate monthly water table contours based on a hybrid, non-linear interpolation scheme. Monthly hydrographs were generated to depict water level elevations over time so that aquifer responses to precipitation, tidal, barometric, and transpiration effects could be evaluated over the area covered by the poplar trees.

A water budget for January 2000 through August 2001 was constructed using the site-specific hydrologic and weather data. The water balance is based on the following equation:

$$P = SR + E + SW + T + GR + `S.$$

Where:

P = Precipitation
SR = Surface Runoff
E = Evaporation
SW = Soil Water
T = Transpiration
GR = Groundwater Recharge
`S = Change in Storage (soil water and aquifer)

Components of the analysis were computed using different hydrologic models. Evapotranspiration was estimated based on the Penman and Thornthwaite methods (Schroeder et al., 1994). Transpiration rates were calculated based on the sap flow measurements that were subsequently scaled to the monthly evapotranspiration calculations to provide transpiration estimates for months where no sap flow data exist. In addition, transpiration rates were estimated for several months based on the diurnal cycles observed in the groundwater hydrographs using methods presented by White (1932). Groundwater recharge estimates generated with the HELP model were used as input into a transient groundwater flow model (MODFLOW) that is being developed to evaluate seasonal variations in hydraulic containment generated by the poplar trees (McDonald and Harbaugh, 1988). Details of the initial steady-state MODFLOW groundwater model are presented in Schneider et al. (2000). Periodically, soil moisture measurements were collected from soil cores. For months where no soil moisture data existed, soil moisture and surface runoff were estimated using the HELP model.

RESULTS AND DISCUSSION

The hydrologic analysis conducted for the J-Field site has yielded compelling evidence to show that the poplar trees are providing seasonal hydraulic containment of the VOC groundwater plume. Continuous monitoring of fluid pressures in the surficial aquifer has demonstrated that the poplar trees are influencing groundwater flow conditions and slowing the migration of the VOC plume. Water table maps illustrate that a cone of depression begins to form beneath the phytoremediation system by late May and extends to early November. An example water table map for September 2001 is presented in Figure 1. From mid-summer through early fall, groundwater levels decline rapidly due to low precipitation and high transpiration rates. A groundwater deficit develops as water levels decline below the adjacent freshwater marsh. This hydrologic event leads to a groundwater flow reversal (boundary effect) where the marsh begins recharging the surficial aquifer. Conversely, during the dormant season, no residual cone of depression exists beneath the trees and groundwater discharges to the marsh. Aquifer efficiency calculations indicate that the surficial aquifer is not influenced by tidal and barometric pressure changes within the area of the phytoremediation system.

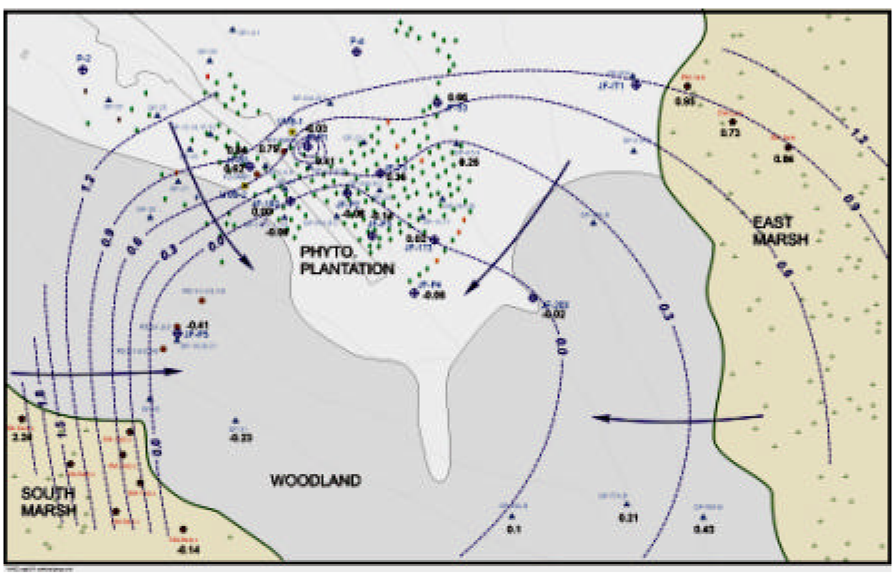

FIGURE 1. September 2001 water table map.

The hydrograph analysis demonstrates that transpiration is a significant groundwater sink during summer. Daily water table cycles were observed from April through September with peak amplitude of 0.25 ft (0.076 m) (Figure 2). Statistical analysis shows that during the growing season, the peak water table decline occurs at 1730, whereas the peak recovery occurs at 0400. During the non-growing season, water levels demonstrate widespread scatter and no discernable cycles. The lag between peak solar radiation and the observed peak groundwater decline is attributed to water storage in the trees and aquifer characteristics. During the summer, groundwater levels beneath the trees decline below the freshwater marsh and induce a flow reversal (leakage) that dampens the water table cycles. The influence of the trees on the surficial aquifer was observed in well clusters to depths of 25 ft (7.6 m) where hydraulic gradients shifted upwards towards the tree roots. Large trees in adjacent woodlands were shown to exert influence on the water table in combination with the poplar trees.

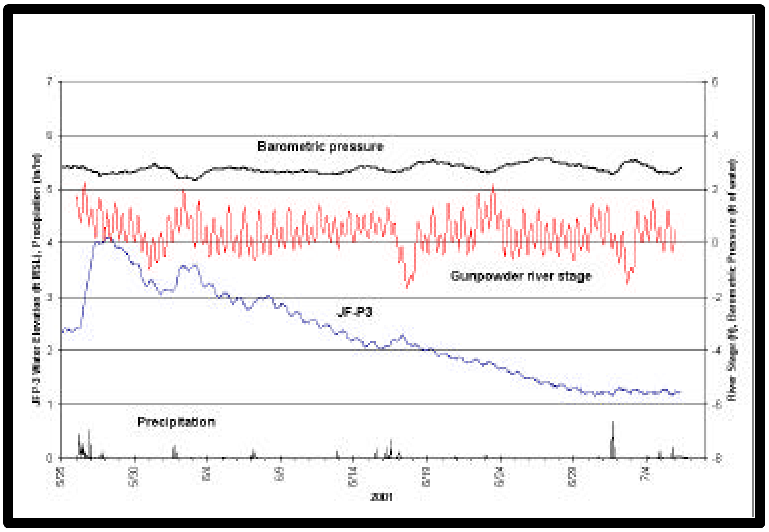

FIGURE 2. Surficial aquifer monitor well JF-P3 hydrograph.

The water budget analysis indicates that during the summer soil moisture levels fall below the wilting point of the trees although the trees show no ill effects. As evidenced by the water table cycles, the trees are dependent upon groundwater for their transpiration stream as evapotranspiration far exceeds precipitation during the summer. The average transpiration rates for the poplar trees range from 1.4 to 10.8 gal/day^{-1}/tree^{-1} (5.3 to 40.9 L/day^{-1}/tree^{-1}), with maximum rates exceeding 21 gal/day^{-1}/tree^{-1} (80 L/day^{-1}/tree^{-1}) (Figure 3). The data are being incorporated into a transient MODFLOW model to predict the seasonal capture zones generated by the poplar trees and to simulate the remedial performance of planting 600 additional trees. The model recently was calibrated and is undergoing a verification test using a 72-hour pump test. Upon completion of this task, a 30-year simulation will be implemented to predict the future hydraulic capture zones.

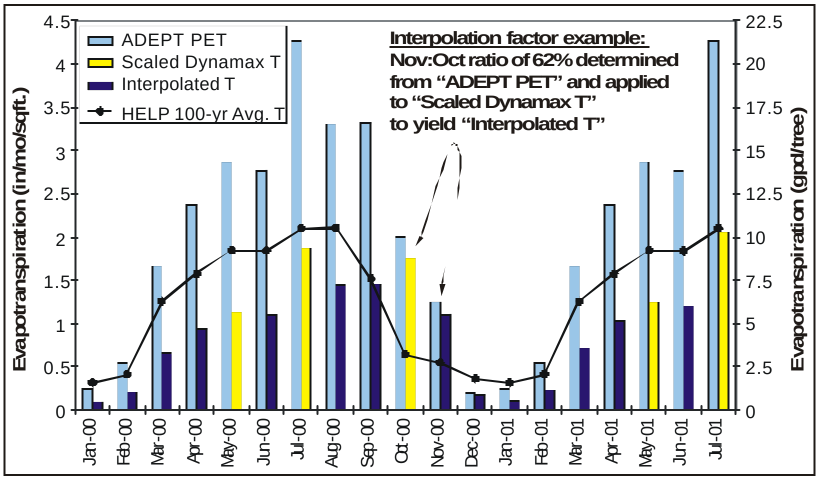

FIGURE 3. Poplar tree transpiration rates.

CONCLUSIONS

The analysis of hydrologic data provides compelling evidence that the poplar trees are successfully containing the shallow, slow-moving groundwater VOC plume from mid-May through early November. The data indicate that the hydrologic system at J-Field is ideal for the application of phytoremediation.

REFERENCES

Burken, J. G. 2001. "Uptake and Volatilization of Chlorinated Solvents by Poplars at Field-Scale." In A. Leeson, E. Foote, K. Banks, and V.S. Magar (Eds.), *Phytoremediation, Wetlands, and Sediments*. Sixth International In Situ and On-Site Bioremediation Symposium (June 4-7, 2001, San Diego, CA). Battelle Press, Columbus, OH.

Burken, J.G. and X. Ma. 2002. *Chlorinated Solvents Phytoremediation: Uptake and Diffusion.* Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds (May 20-23, 2002, Monterey, CA). In Press.

General Physics Corporation. 2001. *J-Field Water Level Measurements Monthly Update.* U.S. Army Garrison, Directorate of Safety, Health and Environment, APG, Maryland, Technical Report, GP-L-711E01296, General Physics Corporation, Edgewood, MD.

Haroski, D.M., S.R. Hirsh, J.G. Wrobel, and H.R. Compton. 2000. "Estimating Hybrid Poplar Groundwater Removal Rates." In G.B. Wickramanayake, A.R. Gavaskar, B.C. Alleman, and V.S. Magar (Eds.). *Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds*. Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds (May 22-25, 2000, Monterey, CA). Battelle Press, Columbus, OH.

Hirsh, S.R., H.R. Compton, D.M. Haroski, J.G. Wrobel, and W.H. Schneider. 2002. "Five-Year Pilot Study: Aberdeen Proving Ground, Maryland. In S.C. McCutcheon and J.L. Schnoor (Eds.), *Phytoremediation: Transformation and Control of Contaminants*. John Wiley and Sons, Inc., New York, NY. In Press.

Kruseman, G.P. and N.A. de Ridder. 1991. *Analysis and Evaluation of Pumping Test Data*. Publication 47, 2nd ed. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Landmeyer, J.E. 2001. "Monitoring the Effect of Poplar Trees on Petroleum-Hydrocarbon and Chlorinated-Solvent Contaminated Ground Water." *International Journal of Phytoremediation*. 3(1):61-85.

McDonald, M.G. and A.W. Harbaugh. 1988. "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model." In *Techniques of Water Resources Investigations*, Book 6, Chapter A1. U.S. Geological Survey, Reston, VA.

Pardue, J., W.A. Jackson, and L. Martino. 2000. *Dialysis Sampler Evaluation of Rhizosphere Phytoremediation Processes in the Poplar Grove of J-Field, APG*. Directorate of Safety, Health and Environment Technical Report. CFR Technical Services, Inc., Baton Rouge, LA, and Argonne National Laboratory, Argonne, IL.

Schneider, W.H., J.G. Wrobel, S.R. Hirsh, H.R. Compton, and D. Haroski. 2000. *The Influence of an Integrated Remedial System on Groundwater Hydrology*. Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds (May 22-25, 2000, Monterey, CA).

Schroeder, P.R., T.S. Dozier, P.A. Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton. 1994. *The Hydrologic Evaluation of Landfill Performance (HELP) Model, 2 Volumes: User's Guide for Version 3, Engineering Documentation for Version 3*. U.S. Environmental Protection Agency Technical Report, EPA/600/R-94/168a,b, U.S. Environmental Protection Agency, Cincinnati, OH.

U.S. Environmental Protection Agency (EPA). 2000. *Introduction to Phytoremediation.* Office of Research and Development Technical Report, EPA1600/R-99/i 07, National Risk Management Research Laboratory, Cincinnati, OH.

White, W.N. 1932. *A Method of Estimating Ground-Water Supplies Based on Discharge by Plants and Evaporation from Soil, Results of Investigations in Escalante Valley, Utah. U.S. Geological Survey Water-Supply Paper 659-A*, 165 p.