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HYDROLOGIC EFFECTS OF COTTONWOOD TREES ON A SHALLOW AQUIFER CONTAINING TRICHLOROETHENE

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ABSTRACT

In April 1996, a field demonstration was begun to evaluate the use of cottonwood trees to help clean up a trichloroethene-contaminated shallow aquifer (< 4 meters below land surface) at the Naval Air Station, Fort Worth, Texas. Transpiration, climate, soil-moisture, and tree-root data were collected and used to parameterize and validate the hydrologic model PROSPER, which was used to simulate evapotranspiration for a 12-year period and to determine the trees' uptake of contaminated water from the saturated zone (aquifer). Simulated annual evapotranspiration from the combined unsaturated and saturated zones ranges from 25 to 48 centimeters for the period when the tree plantations have achieved a closed canopy (year 12 and beyond), depending on assumptions regarding climatic conditions, soil-water availability, and root growth. Simulated annual uptake from the saturated zone for year 12 and beyond ranges from 12 to 28 centimeters. The ground-water flow model MODFLOW was used to simulate the effects of this predicted transpiration on ground-water flow in the aquifer. Although transpiration from the aquifer is predicted to reach between 50 and 90 percent of the initial volumetric flux of ground water through the demonstration site, the outflow of contaminated ground water from the site will likely be reduced by only 20 to 30 percent. The discrepancy between predictions for volume of water transpired from the aquifer and the reduction in volumetric outflow of contaminated ground water can be attributed to a predicted increase in ground water inflow to the site and the release of water from storage in the aquifer. It may be possible to achieve a greater amount of hydraulic control if additional trees are planted.

BACKGROUND

A field-scale demonstration designed to test the ability of eastern cottonwood trees to help clean up shallow trichloroethene (TCE) contaminated ground water was begun in April 1996 by the U.S. Air Force Aeronautical Systems Center Environmental Safety and Health Division Engineering Directorate. The principal objective of the demonstration project was to generate cost and performance data related to this application of phytoremediation for the purpose of technology transfer.

The site selected for the demonstration project is on the Carswell Golf Course at the Naval Air Station Fort Worth, about 1 mile from the main assembly building at Air Force Plant 4 in Fort Worth, Texas. The assembly building is the primary suspected source of TCE in the ground water at the demonstration site (RUST Geotech Inc., 1993). The aquifer at this location is a silty sand with a saturated thickness of 0.5 to 1.5 meters (m). The geometric mean of the horizontal-hydraulic conductivity values determined for the site is 7 x 10^{-3} cm/s. The water table at the site is typically between 2.5 and 4 m below land surface. The hydraulic gradient across the site was just over 2 percent during site characterization. TCE concentrations in the ground water during site characterization ranged from 230 to 970 micrograms per liter (ug/L).

Approximately 440 whips (sections of 1-year old stems harvested from branches during the dormant season) and 220 cottonwood trees of 2.5 - 3.8 centimeter (cm) caliper (trunk diameter) were planted in two separate plantations at the demonstration site. Each plantation is 15 by 75 m and is oriented approximately perpendicular to the direction of ground-water flow. The plantations span the most concentrated part of the underlying finger of the plume. The size of the plantations was constrained, in part, by the demonstration nature of the study. More than 60 wells were installed to monitor ground-water levels and chemistry at the demonstration site and surrounding area (figure 1). Tree collars and probes were installed periodically on selected trees to measure sapflow.

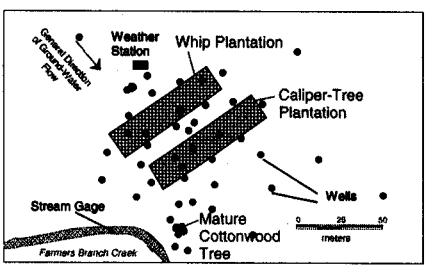

FIGURE 1. Demonstration-site design.

MEASURES OF PERFORMANCE

The performance of the phytoremediation treatment system was measured by calculating changes in the mass flux of TCE across the downgradient end of the planted area over the course of the 3-year demonstration. TCE mass flux is defined as follows:

TCE Mass Flux = Volumetric Flux (of Ground Water) x TCE Concentration; where (1)
Volumetric Flux = Hydraulic Conductivity x Hydraulic Gradient x Aquifer Thickness x Aquifer Width. (2)

Because transpiration of water from the aquifer has the ability to affect the volumetric flux of ground water, the hydrologic effects of the trees on the contaminated aquifer were assessed by monitoring the volumetric flux of ground water across the downgradient end of the planted area. The wells used to determine the hydraulic gradient for the volumetric flux calculations (wells 522 and 529) were chosen so that they did not reflect increases in hydraulic gradient across the upgradient end of the site (figure 2). A corresponding potentiometric-surface map for each

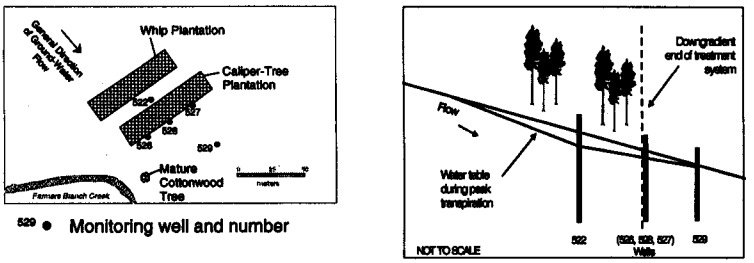

FIGURE 2. Wells used to monitor for changes in the volumetric flux of ground water.

selected time was consulted to verify that changes in hydraulic gradient computed using these two wells were due to the influence of the trees rather than to variations in the direction of ground-water flow. The thickness of the aquifer at each selected time was computed by averaging the saturated thickness in the wells immediately downgradient of the tree plantations (wells 526, 527, 528). The saturated thickness in each of these three wells was first normalized to wells in the surrounding area to account for temporal changes in the saturated thickness of the aquifer unrelated to the planted trees. Specifically, water-level data at each selected time were adjusted by an amount equal to the difference between the water level at the selected time and the water level at baseline (November 1996) in wells outside the influence of the planted trees. (November 1996 was used to represent baseline conditions in the aquifer because the most comprehensive set of water-level and ground-water chemistry data for the period before the tree roots reached the water table were collected at this time.) The aquifer width that was used in the volumetric-flux calculations is 75 m, which is the length of the tree plantations. A value of 7×10^{-3} cm/s was used for hydraulic conductivy.

The percent change in the volumetric flux of ground water across the downgradient end of the site that can be attributed to the trees was computed by comparing the volumetric flux of ground water computed for each selected time to the volumetric flux of ground water computed for baseline conditions.

$$\text{Volumetric Flux Change}_{(\text{event x})}\,(\%) = \frac{(\text{Volumetric Flux}_{(\text{baseline})} - \text{Volumetric Flux}_{(\text{event x})})}{\text{Volumetric Flux}_{(\text{baseline})}} \times 100 \text{ ; where } (3)$$

Event x is peak (end of June or beginning of July) of the growing season 1997, 1998, or 1999, or late (end of September or beginning of October) in the growing season 1997 or 1998.

HYDROLOGIC EFFECTS OF THE COTTONWOOD TREES

Observed Effects

Excavation revealed that the tree roots in both plantations reached the water table some time during the second growing season (1997) (R. Hendricks, Univ. of Georgia, written commun., 1998). A measured decrease in the hydraulic gradient and the normalized saturated thickness of the aquifer at the downgradient end of the site during the second season indicated that transpiration was affecting the volumetric flux of ground water out of the demonstration site at this time. Table 1 summarizes the effects of the trees on the volumetric flux of ground water across the downgradient end of the planted area during the course of the study. The planted trees reduced the outward flux of ground water by 5 percent during the peak of the second season. Reductions were 12 and 8 percent during the peak of the third and fourth growing seasons, respectively. Variations in climatic conditions resulted in the differences between the third and fourth seasons.

Event	Hydraulic Gradient (dimensionless)	Cross Sectional Area (m^2)	Volumetric Flux (m^3/d)	Change in the Volumetric Flux Attributed to the Planted Trees
Baseline	0.0159	84	8.0	--
Peak 2nd Season	0.0154	82	7.6	-5%
Late 2nd Season	0.0157	83	7.8	-2%
Peak 3rd Season	0.0143	82	7.0	-12%
Late 3rd Season	0.0150	83	7.5	-6%
Peak 4th Season	0.0153	81	7.4	-8%

TABLE 1. Effects of the trees on the volumetric flux of ground water.

The maximum drawdown that can be attributed to the trees during the study is 10 cm and was observed between the two tree plantations at the peak of the third growing season. Although a drawdown cone could be mapped at the water table at this stage of the system's development, there remained a regional hydraulic gradient across the site that resulted in most of the ground water flowing outward across the downgradient end of the planted area (figure 3).

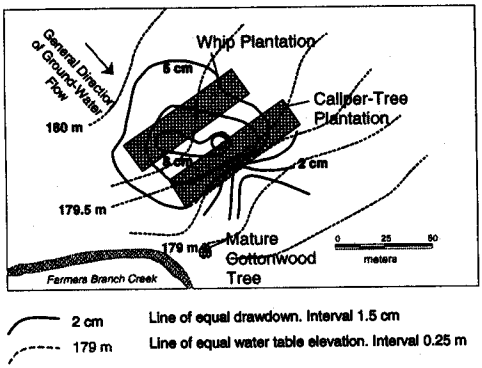

FIGURE 3. Drawdown at the water table that can be attributed to the trees, June 1998.

Simulated Effects

Because the planted trees were not expected to reach their transpiration potential during the course of the study, a modeling approach was necessary to predict future system performance. The hydrologic model PROSPER (Goldstein and others, 1974) was used to simulate future transpiration at the demonstration site. Predicted evapotranspiration for 2007, when the trees are expected to achieve closed canopy and reach their maximum transpiration potential, ranges from 25 to 48 cm, depending on assumptions related to climatic conditions, soil-water availability, and root growth. A root biomass study at the site (R. Hendricks, Univ. of Georgia, written. commun., 1998) was used to help determine the percentage of this transpired water that may be derived from the aquifer. Predicted transpiration from the aquifer ranges from 12 to 28 cm for 2007 and beyond; this is 48 to 58 percent of predicted evapotranspiration.

A ground-water flow model of the demonstration site was constructed using MODFLOW (McDonald and Harbaugh, 1998) to help in understanding the observed effects of tree transpiration on the aquifer and to predict the effects of the future increases in transpiration rates on ground-water flow. The model illustrates that the volume of water that was transpired from the aquifer during 1998 was greater than the reduced outflow of water that can be attributed to the trees. This is because of an increased amount of ground-water inflow to the demonstration site due to an increase in hydraulic gradient on the upgradient side of the drawdown cone created by the trees. The amount of contaminated water that was transpired from the aquifer during the peak of the 1998 growing season (third season) was equal to an amount closer to 20 percent of the initial volumetric flux of water through the site rather than the simulated decrease in outflow of approximately ten percent (figure 4A,B).

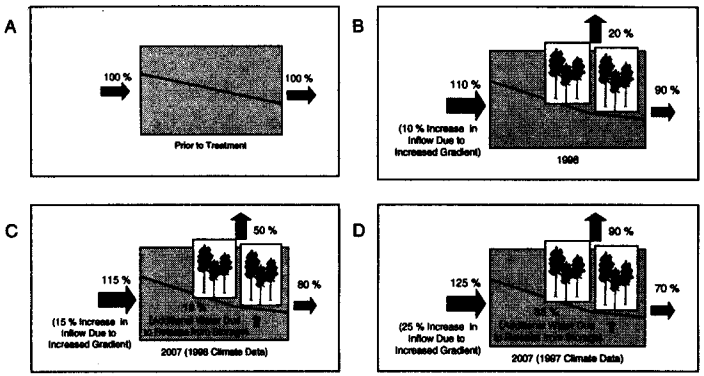

FIGURE 4. Simulated ground-water budget (A) prior to treatment, (B) peak of the 1998 growing season, (C) peak of the 2007 growing season with climatic conditions similar to 1998, and (D) peak of the 2007 growing season with climatic conditions similar to 1997.

The predicted decrease in the volumetric flux of ground water across the downgradient end of the planted area for 2007 ranges from 20 to 30 percent of the flux through the site prior to treatment. The predicted volume of water that is transpired from the aquifer, however, ranges from 50 to 90 percent of the initial volumetric flux (figure 4A,C,D). The discrepancy between the reduction in the outward volumetric flux of ground water and the volume of water transpired from the aquifer can be attributed to the release of water from storage in the aquifer and an increase in hydraulic gradient on the upgradient side of the drawdown cone, which leads to increased inflow to the site.

These model results indicate that a regional hydraulic gradient will remain across the planted area during future growing seasons. The volumetric flux of ground water across the downgradient end of the planted area, however, will be notably reduced during the growing season. As a result, the TCE mass flux will be reduced. Percent reductions in the TCE mass flux due to tree transpiration will be somewhat less than reductions in the volumetric flux of ground water because membrane barriers at the root surface prevent TCE from being taken up at the same concentration as it occurs in the ground water. The transpiration stream concentration factor or fractional efficiency of uptake for TCE has been reported to be 0.74 (Schnoor, J.L., 1997). No hydraulic control of the plume is predicted for the dormant season (November through March). It may be possible to achieve a greater amount of hydraulic control if more trees are planted but increased inflow and release of water from storage in the aquifer will continue to be factors that affect hydraulic control of the contaminant plume.

SUMMARY

Hydrologic effects of cottonwood trees on a shallow TCE-contaminated aquifer were evaluated as part of a field-scale demonstration of phytoremediation. Changes in the hydraulic gradient and saturated thickness of the aquifer that can be attributed to the trees were observed as early as the second growing season. A maximum of 10 cm of drawdown was observed during the third season. This amount of drawdown corresponds to a maximum observed reduction in the volumetric flux of ground water across the downgradient end of the planted area of 12 percent.

A ground-water flow model of the demonstration site was constructed to help in understanding the observed effects of tree transpiration on the aquifer and to predict the effects of simulated increases in transpiration rates on ground-water flow. There is a range of predictions because of expected variations in climatic conditions, as well as assumptions related to soil-water availability and root growth. The volumetric flux of ground water across the downgradient end of the planted area is predicted to decrease by 20 to 30 percent during the peak of the growing season once the tree plantations have achieved a closed canopy (2007). Transpiration from the aquifer in 2007 is predicted to range from 50 to 90 percent of the volume of ground water that flowed through the demonstration site before the trees were planted. The discrepancy between the predictions for the reduction in the volumetric outflow of ground water and the volume of water transpired from the aquifer can be attributed to a predicted increase in ground-water inflow and release of water from storage in the aquifer. The trees that were planted for this demonstration will not be able to achieve full hydraulic control of the underlying finger of the plume; more hydraulic control may be possible if more trees are planted.

ACKNOWLEGEMENTS

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