Fate and Transport of a TCE Groundwater Contamination Plume

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Abstract

The world's largest plume of trichloroethylene (TCE) contamination has polluted drinking water wells in Mancelona, a rural, low-income community in northern Michigan. The TCE plume is venting into the Cedar River which flows into Lake Bellaire, which ultimately discharges into Lake Michigan. TCE levels as high as 500 ppb were detected in the 121 permanent monitoring wells that were installed to monitor TCE concentrations in groundwater and the change in TCE levels over time. The aim of this study is to model the extent of the TCE plume to help assess the environmental impact on the aquifer. BIOCHLOR model from the Environmental Protection Agency (EPA) is used to model the fate and transport of the contaminant. The model simulates the advective transport based on the past movement of plume. The results show that the model follows the sampling data previously collected. Modeling the plume is of vital importance as it predicts the time it takes for TCE to reach Lake Michigan and contaminates the drinking wells along its path.

Introduction

The world's largest plume of trichloroethylene (TCE) contamination, extending about 6 miles over 4,000 acres, has polluted drinking water wells in Mancelona, a rural, low-income community in northern Michigan [1]. Mancelona, MI has a population of 1,360 people and a median household income of $34,688 [2].

The contaminated aquifer is estimated at 13 trillion gallons. Mount Clemens Industries, Inc., later known as Wickes Manufacturing, used TCE as a degreasing solvent and dumped it in the shallow sandy pits in Mancelona from 1947 to 1967 [1]. Waste containing TCE was discarded on the ground and in lagoons, where it seeped through the soil and became dissolved into the groundwater. Both companies went out of business many years ago. Currently, Mancelona residents rely on a temporary municipal water system that the state of Michigan connected to residences in order to provide safe drinking water.

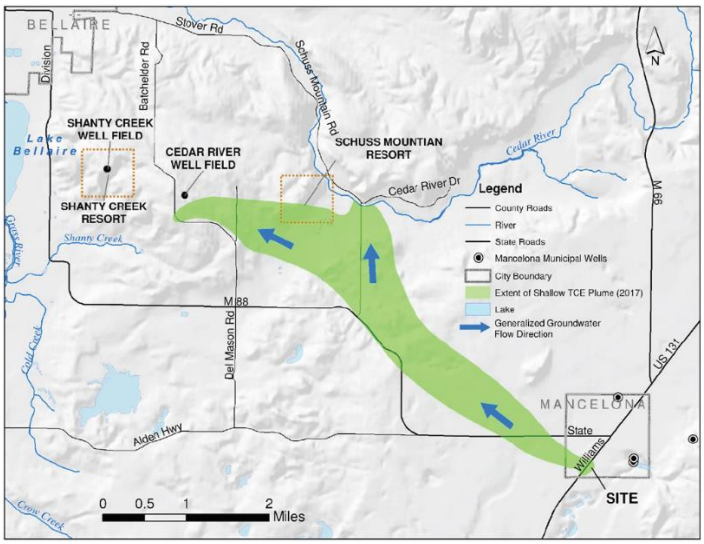

Figure 1. Mapping of the TCE plume with groundwater flow direction [1].

The TCE plume is venting into the Cedar River which flows into Lake Bellaire, which ultimately discharges into Lake Michigan. There are 121 permanent monitoring wells that have been installed by the Michigan Department of Environmental Quality (MDEQ) to determine groundwater flow direction and rate, where TCE occurs in groundwater, and how TCE levels in groundwater change over time. Each year, during the spring and fall, the DEQ collects groundwater samples from select monitoring wells and sends them for laboratory analysis. Monitoring well sampling of the groundwater is critical to providing early warning of TCE movement in groundwater. TCE has been detected in groundwater in some locations as deep as 500 feet below the ground. The exact depth of TCE in groundwater at any given location depends on the local ground topography. The maximum contaminant level of TCE in drinking water is 5 parts per billion (ppb), and TCE concentrations in groundwater below 200 ppb can safely flow into or vent to surface water, such as rivers, lakes or wetlands. However, TCE levels as high as 500 ppb were detected [1].

TCE is a known human cancer-causing agent [3]. People who breathe moderate levels of TCE may have headaches or dizziness [4]. However, long term exposure can adversely affect liver, kidney, immune system and/or central nervous system functions [5]. Effects of TCE can result from low-level exposure over long periods of time (many years) or over short time frames at high concentrations [6]. Long term inhalation of TCE is a human health concern [7]. Moreover, TCE is a volatile organic compound, meaning that it readily changes from a liquid to a vapor. This property causes TCE to move from surface water bodies, like the Cedar River, to the air. This same property works underground; TCE dissolved in groundwater can become a vapor and move into the air space in the soil above the water table. TCE vapors may get into homes through openings in basements such as cracks, or other openings around pipes and sumps. This is a concern because residents may breathe in these harmful vapors without knowing. Depending on the amount and type of chemicals, even a short time of breathing them can cause long-term

and serious health problems [8]. When TCE dissolved concentrations in groundwater reach levels above 2,200 parts per billion (ppb), it may adversely affect indoor air quality when groundwater is more than 10 feet below the building [9].

Methods

A transport model was used to analyze the natural attenuation of TCE. A spatio-temporal analysis of water data was performed, and interpolation and visualization of the distribution of pollutant concentration over space and time was done. BIOCHLOR from EPA was used to model the fate and transport of the contaminant [10]. As the modeling tool picked,

BIOCHLOR Natural Attenuation Decision Support System is a screening model that simulates natural attenuation of dissolved solvents in groundwater. The software is based on a sequential, first-order, coupled reactive transport model. The transport problem is analytically solved using the modified Domenico model with first order biotransformation and source decay. The original Domenico model simulates the release of organic chemicals to moving ground water by assuming one-dimensional advective transport, three-dimensional dispersion, linear adsorption, and first-order decay [10]. In BIOCHLOR, the modified Domenico solution that was used provides a simulation of advective transport with no decay, which is appropriate for predicting the movement of conservative (non-degrading) solutes. The only attenuation mechanisms are dispersion in the longitudinal, transverse, and vertical directions, as well as adsorption of contaminants to the soil matrix if applicable [10].

$$C(x,y,z,t) = \frac{C_O}{8} f_x f_y f_z$$

$$f_x = \exp\left(\frac{x\left[1-\left(1+4\lambda\alpha_x/v_s\right)^{0.5}\right]}{2\alpha_x}\right) * erfc\left(\frac{x-vt\left(1+4\lambda\alpha_x/v_s\right)^{0.5}}{2\left(\alpha_x vt\right)^{0.5}}\right) +$$

$$\exp\left(\frac{x\left[1+\left(1+4\lambda\alpha_x/v_s\right)^{0.5}\right]}{2\alpha_x}\right) * erfc\left(\frac{x+vt\left(1+4\lambda\alpha_x/v_s\right)^{0.5}}{2\left(\alpha_x vt\right)^{0.5}}\right)$$

$$f_y = \mathrm{erf}\left(\frac{(y+Y/2)}{2\left(\alpha_y x\right)^{0.5}}\right) - \mathrm{erf}\left(\frac{(y-Y/2)}{2\left(\alpha_y x\right)^{0.5}}\right) \qquad f_z = \mathrm{erf}\left(\frac{z+Z}{2\left(\alpha_z x\right)^{0.5}}\right) - \mathrm{erf}\left(\frac{(z-Z)}{2\left(\alpha_z x\right)^{0.5}}\right)$$

Figure 2. Domenico Single Species Analytical Model [10].

C(x, y, z, t), concentration at distance x downstream of source and distance y off centerline of plume at time t (mg/L).

Co, concentration in Source Area at t=0 (mg/L).

x, distance downgradient of source (ft).

y, distance from plume centerline of source (ft).

z, distance from top of saturated zone to measurement point (assumed to be 0; concentration is always given at top of saturated zone).

α_x, longitudinal ground-water dispersivity (ft).

α_y, transverse ground-water dispersivity (ft).

α_z, vertical ground-water dispersivity (ft).

θ_e, Effective Soil Porosity.

λ, First-Order Degradation Rate Coefficient (day-1).

v_s, Seepage Velocity (ft/yr)=$Ki/(\theta_e)$.

v, Chemical Velocity (ft/yr)= v_s/R.

K, Hydraulic Conductivity (ft/yr).

R, constituent retardation factor.

i, Hydraulic Gradient (cm/cm).

Y, Source Width (ft).

Z, Source Depth (ft).

BIOCHLOR uses the Domenico solution with Martin-Hayden and Robbins improvements and assumes that degradation reactions occur only in the aqueous phase [10]. BIOCHLOR evaluates centerline concentrations at y=0, z=0 and the 2-D array at z=0. The initial conditions of the Domenico model are i) C(x, y, z, 0) = 0 (Initial concentration = 0 for x, y, z, > 0), ii) C(0, Y, Z, 0) = C_0 (Source concentration for each vertical plane source = C_0 at time 0) [10].

The key assumptions in the model are that the aquifer and flow field are homogeneous and isotropic; the ground-water velocity is fast enough for the molecular diffusion in the dispersion terms to be ignored; and adsorption is reversible and represented by a linear isotherm [10].

The model should not be applied when pumping systems are present, or when vertical flow gradients affect contaminant transport, or in the situation where hydrogeological conditions change dramatically over the simulation domain [10].

Results and Discussion

A total of eleven monitoring wells along the TCE plume centerline were picked for data collection. These wells form a path stretching from the source of the contamination to the head of the plume which is venting northwest. Figure 3 shows the plume extent with the monitoring wells that were used for modeling purposes.

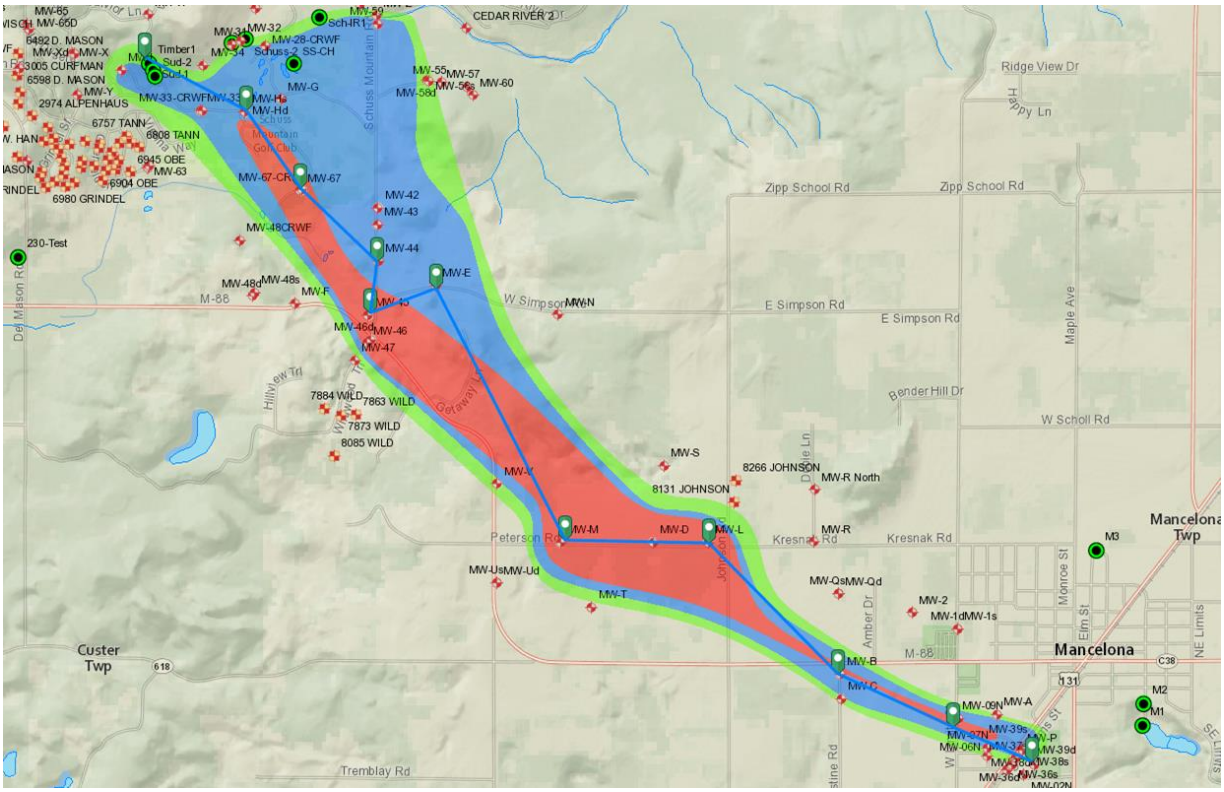

Figure 3. TCE plume of 2004 to 2005 with 11 monitoring wells picked along centerline [11].

Figure 4 displays the concentrations of TCE for the 11 wells with respect to their distance from the point source of the contamination for data collected in 2004-2005.

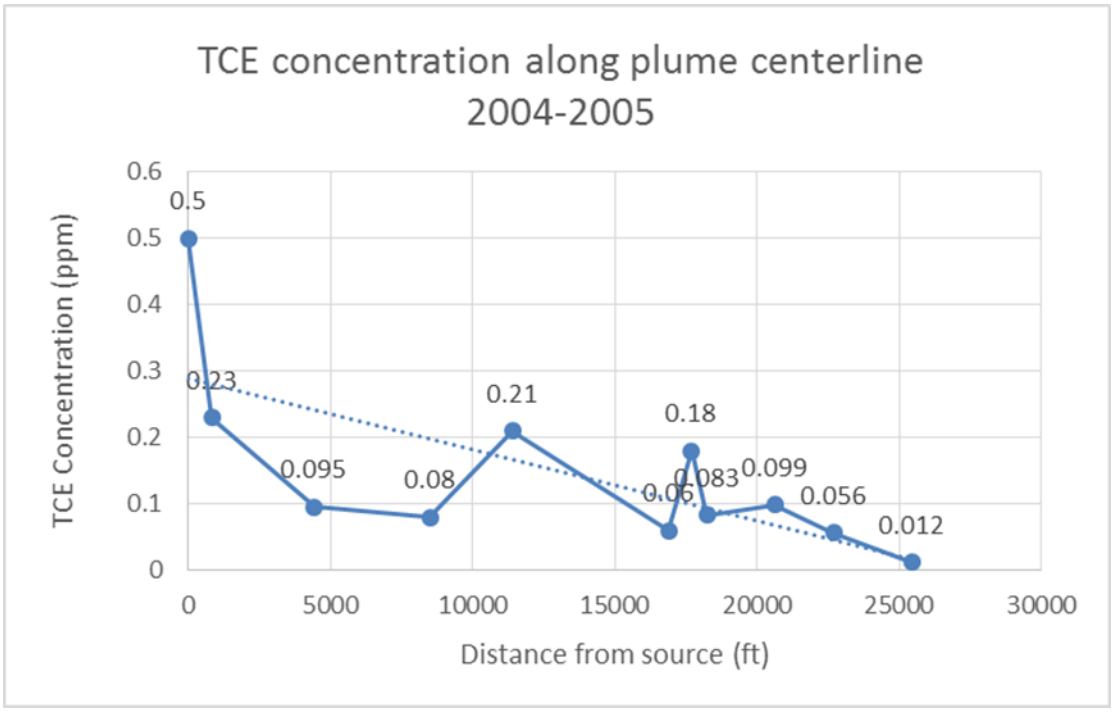

Figure 4. TCE concentration vs. Distance from 2004 to 2005.

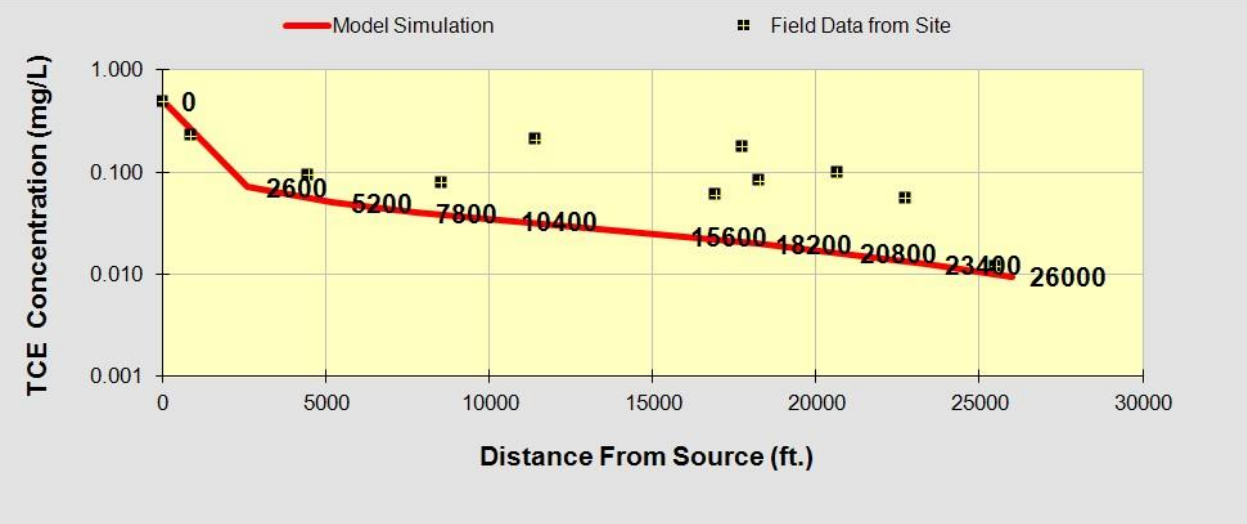

Figure 5. Modeling results for a 50-year time simulation based on 2004-2005 data.

TCE movement with the groundwater varied with depth. In the shallow zone, TCE advection rate was estimated between 300 and 400 feet per year, whereas in the intermediate zone, the rate was much slower (100 feet per year). A comparison of TCE concentrations among the monitoring wells in the deep zone showed no spreading or movement. The 11 monitoring wells in this study were in the shallow zone. Using the EPA BIOCHLOR modeling tool, figure 5 displays the result of a 50-year time simulation based on the TCE concentrations from 2004 to 2005. Although, the model does not follow the concertation trend very closely, it predicts that the TCE concentration of the original source would decrease to about 30 ppb as the plume travels 18,000 feet after 50 years. This concentration, although lower than the original one, is still above the 5 ppb maximum allowable contaminant level of TCE in drinking water.

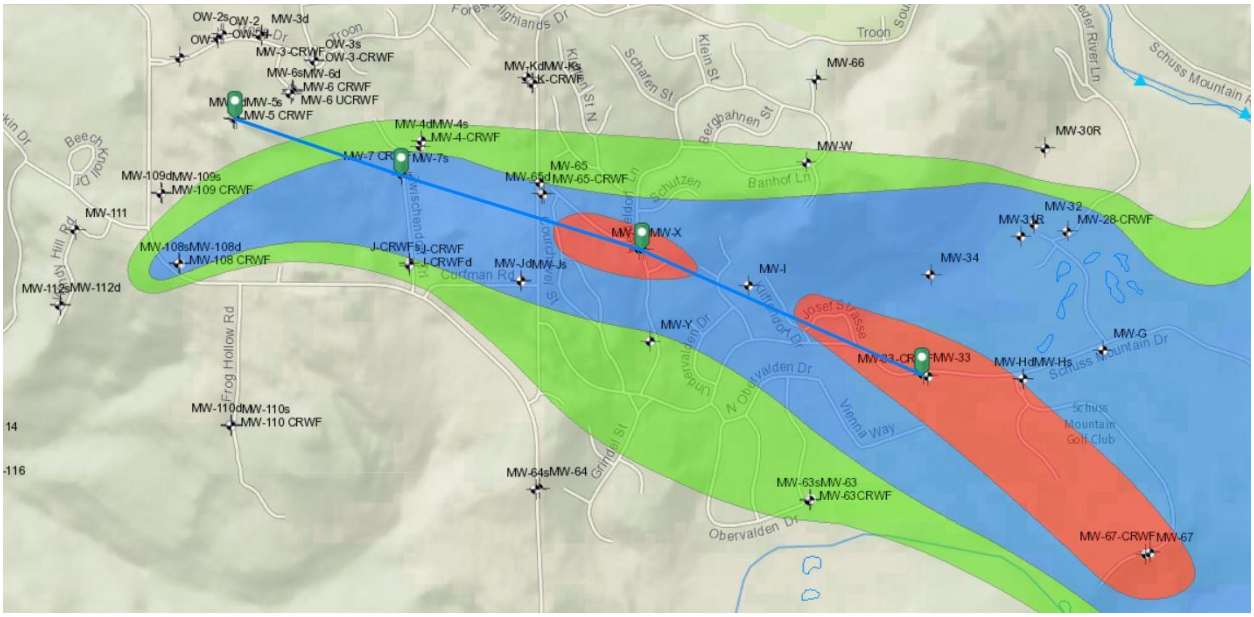

Figure 6. West Lobe TCE plume of 2016 with 4 monitoring wells picked along centerline [11].

With the direction of the plume pointing west, concerns emerged with the west lobe of the plume which is the leading plume mass venting eventually to Lake Michigan. Recent data from 2016 monitoring wells became available and were used for further studies of the plume movement. Four wells in the center line of the west lobe were picked for modeling as displayed in Figure 6.

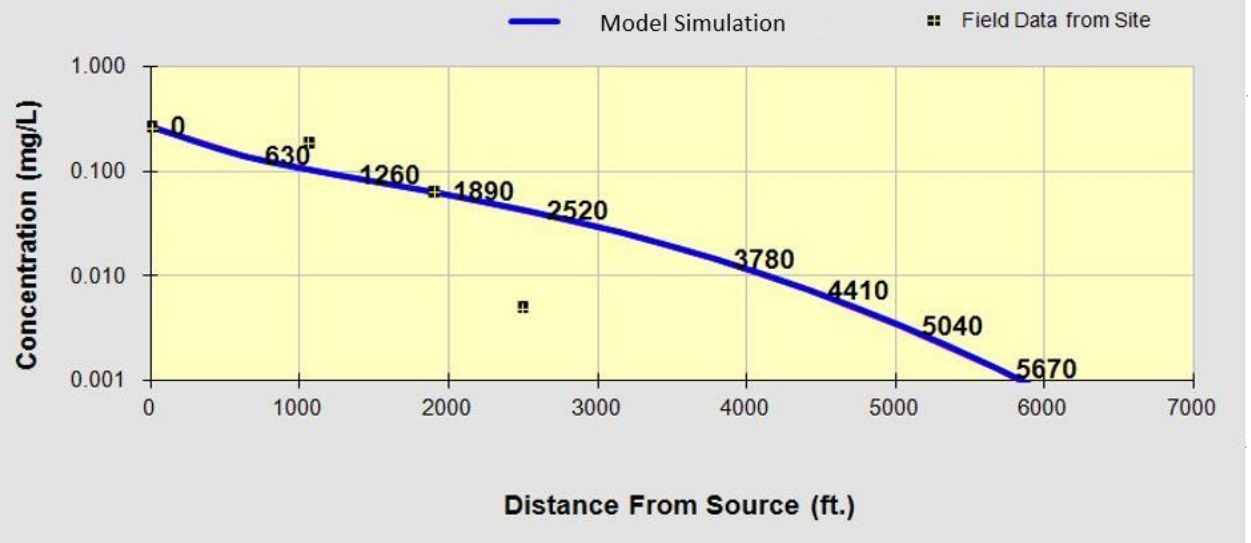

Figure 7. West lobe TCE modeling results for a 5-year time simulation based on 2016 data.

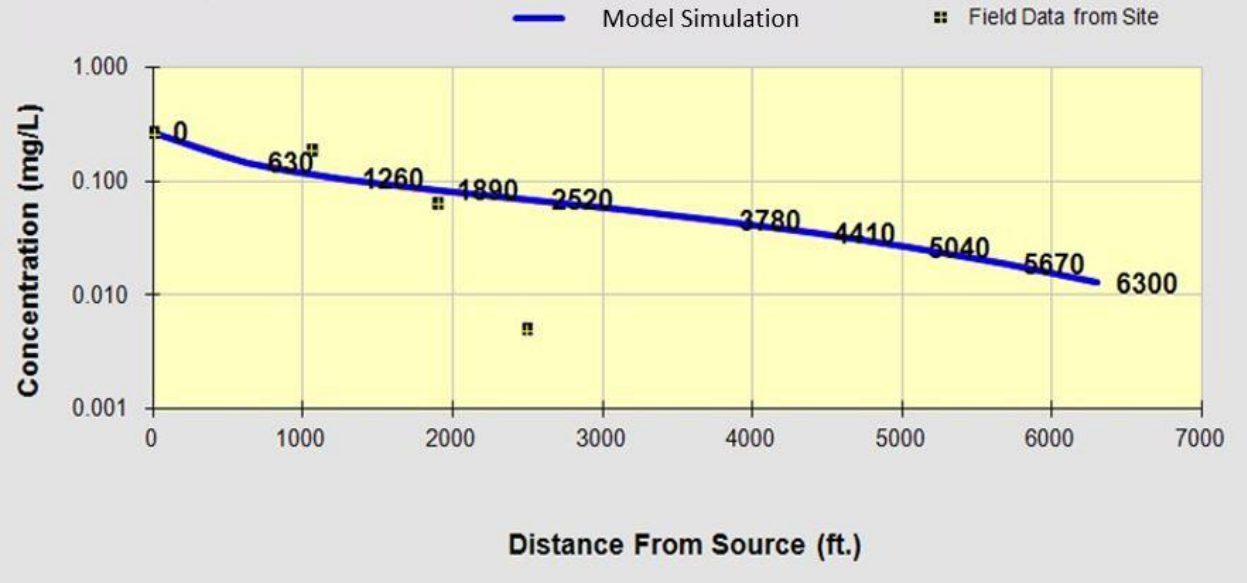

Figure 8. West lobe TCE modeling results for a 10-year time simulation based on 2016 data.

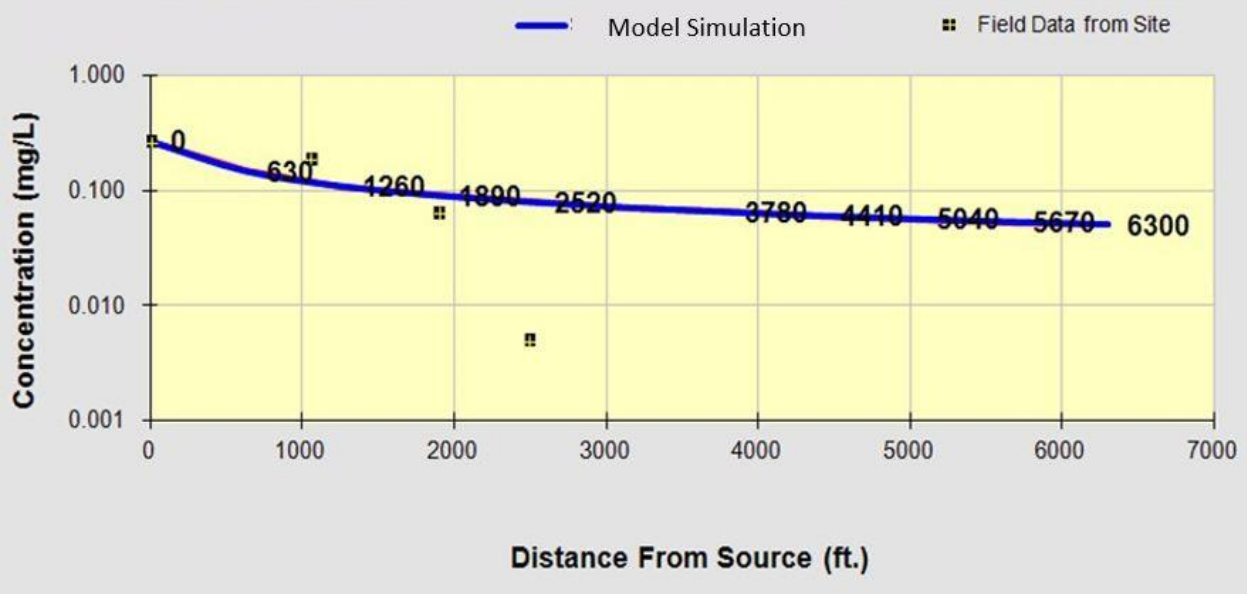

Figure 9. West lobe TCE modeling results for a 50-year time simulation based on 2016 data.

Figures 7, 8 and 9 model the TCE concentrations of the west lobe plume for the next 5, 10, and 50 years based on the 2016 data. In 5 years, figure 7 predicts that the center mass of the west lobe plume will be located 1800 feet from it was in 2016, and the concentration will become around 100 ppb. Figures 8 and 9 show that the model is predicting a lower concentration at the center mass of the plume for the 10 and 50-year simulation compared to the current concentrations. Although the concentrations are lower, they are still above the maximum contaminant level as the plume travels closer to Lake Michigan.

Conclusion

A multi-dimensional transport model was developed to analyze the natural attenuation of TCE. A spatio-temporal analysis of water data was performed and modeled using EPA BIOCHLOR modeling program. Interpretation of the simulation results shows that although the model followed the concentration trend in general, more refinement is needed to accurately predict the plume transport and fate.

Current work in progress includes the interpolation and visualization of the distribution of pollutant concentrations over space and time using space-timing krinking. The new model will be calibrated to field data collected at this site and tested to see if the calibrated model can more closely reproduce the observed distribution of TCE.

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