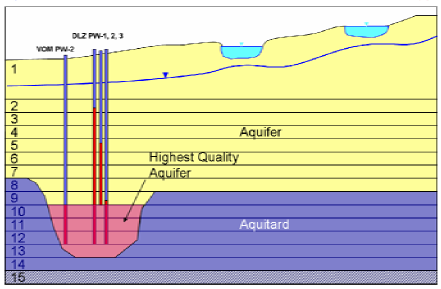
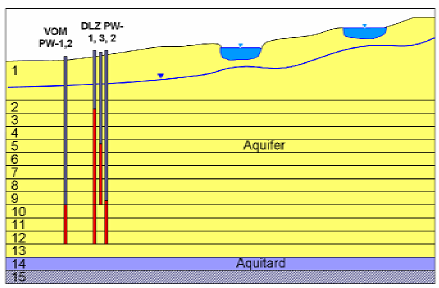


When Does Aquifer Heterogeneity Matter? Predicting the Influence of Alternative Conceptual Models on Contaminant Plume Migration



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Synopsis: In this classroom activity, students are given two alternative conceptualizations of aquifer/aquitard distributions in a glacial aquifer system and asked to predict differences in the migration of contaminant plumes in response to remedial pumping.

Intended audience: This exercise is appropriate for an upper division undergraduate or graduate level course in hydrogeology incorporating single phase subsurface flow and transport.

Students should have mastered:

- Concepts of aquifer and aquitard (aquifer heterogeneity).
- Darcy's law and flow in response to equipotential differences in homogeneous aquifers.
- Single phase transport processes for dissolved constituents.

Students should have been exposed to concepts of:

- Drawdown and radial flow in response to pumping.
- Dispersion.
- Breakthrough curves.
- Monitoring and pumping well fundamentals (screened intervals, pumping rates, etc.)

Goals:
Students will:

- explore and expand their understanding of aquifer heterogeneity.
- predict changes in contaminant plume migration in response to pumping.
- evaluate the ability of pumping wells and monitoring wells to detect predicted changes.
- consider the efficacy of performance monitoring well networks in the face of changing stresses to the hydrologic system.

Activity Description: In this exercise, students predict changes in contaminant transport behavior for a dissolved plume in response to remedial pumping in an unconfined aquifer. The underlying conceptual model for the distribution of aquifer and aquitard materials is not known with certainty. Consequently, two alternative end-member conceptualizations are presented to students who are subsequently asked to hypothesize differences in responses measured at the pumping wells and nearby monitoring wells. Predictions are compared to actual field data, and students discover that contaminant concentration measurements depend not only on the location of the observation point (in three dimensions), but also on the length of the screened interval through which water samples are collected. The activity is divided into three parts: (1) site/problem description, (2) formulation and testing of hypotheses for pumping wells, and (3) formulation and testing of hypotheses for monitoring wells. The activity gives students practice in three dimensional thinking and reinforces their intuitive understanding of contaminant plume migration in response to natural gradients and engineered stresses.

<u>Part 1. Site/Problem Description</u>

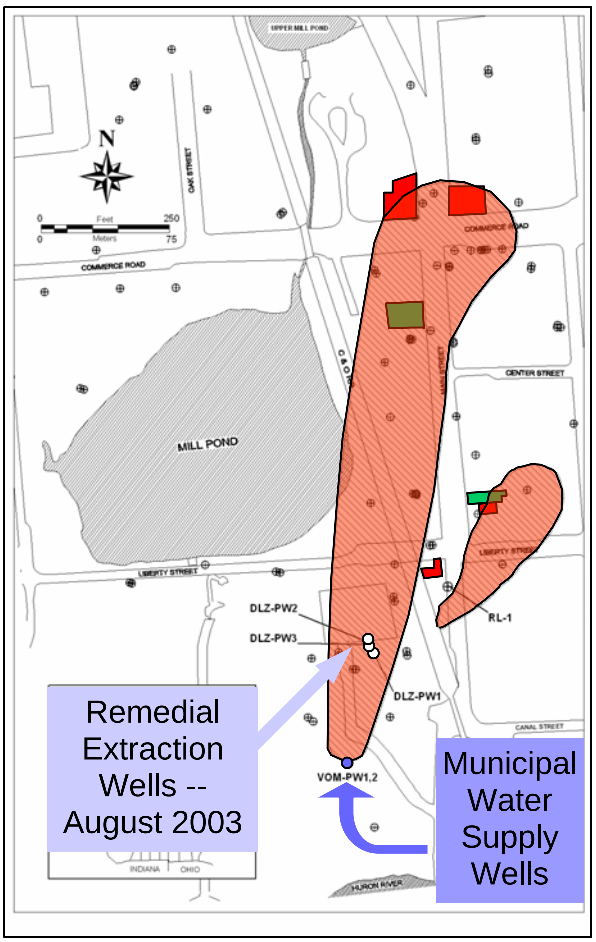

Figure 1. Location map showing VOC contaminant plumes, identified source areas (red = MTBE, green = cDCE), and location of municipal water supply and remedial pumping wells.

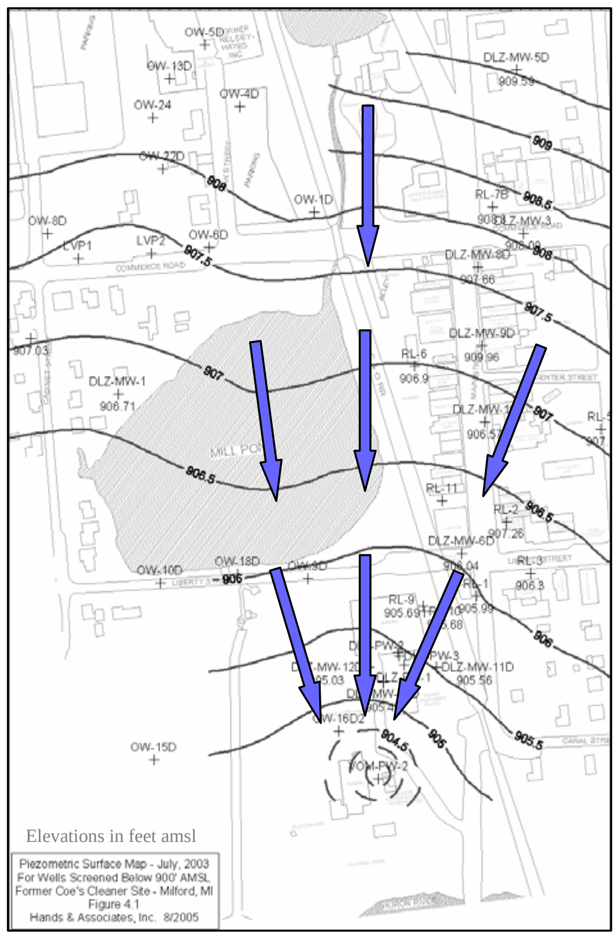

Figure 2. Piezometric surface (water table) map for the unconfined aquifer showing cone of depression around VOM municipal water supply wells. Arrows denote the general direction of groundwater flow.

The Village of Milford, Michigan is located in the region of surficial glacial drift deposited during the Pleistocene glaciation of North America. Glacial sediments in the vicinity of Milford range from 250 to 350 feet thick and are underlain by the Mississippian Coldwater Shale bedrock (Passero et al., 1981). Groundwater generally flows from north to south and discharges into the Huron River south of the Village of Milford's two municipal water supply wells (VOM PW-1,2). These water supply wells have been operated since the early 1960's. Chemical contaminants have been detected at concentrations below the Michigan Department of Environmental Quality (MDEQ) Residential Drinking Water criteria in the water supply wells. Both wells are screened approximately 100 feet below the ground surface in an unconfined glacial drift aquifer. Two former dry cleaning businesses are thought to be sources of chlorinated solvents and several existing or former gasoline stations are identified as sources of gasoline component contaminants detected in groundwater at the site (MDEQ, July 1998). In August 2003, three nested remedial groundwater extraction wells were installed at the site in a position downgradient of the identified contamination sources and upgradient of the Village of Milford municipal water supply wells in an effort designed to intercept groundwater contaminants migrating toward the water supply wells. The extraction wells began pumping in August, 2003, at a combined rate of approximately 300 gallons per minute (gpm).

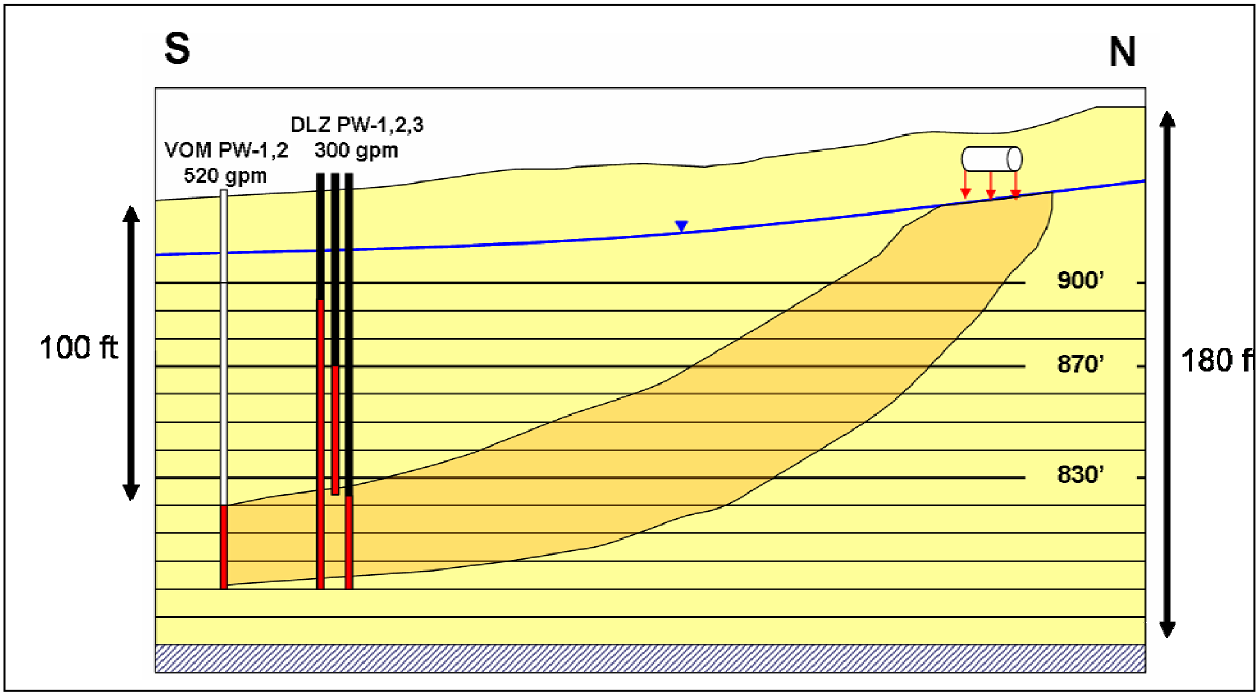

Figure 3. Schematic north-south cross section illustrating the postulated contaminant plume migration path prior to the onset of remedial pumping.

Hydrogeologic investigations conducted over the past decade assumed the presence of a continuous aquitard unit underlying the unconfined aquifer at the site (Techna, 1999, DLZ, 2002). However, the geometry of the interface between the unconfined aquifer system and the underlying aquitard is defined by a limited number (eight) of deep wells reported to have terminated in low permeability soil units (Hands, 2005). Six of these eight wells penetrated 5 feet or less of potential aquitard material prior to reaching their total depth. Because of the documented presence of thin fine-grained sediment intervals in other site soil borings, these six wells do not define unequivocally the presence and location of an extensive and laterally continuous aquitard unit. Consequently, two alternative end-member conceptual models for the geometry of the aquifer/aquitard contact have been proposed, each consistent with available subsurface control points. These are referred to as the *Regional Aquitard* and *Extended Aquifer* Models.

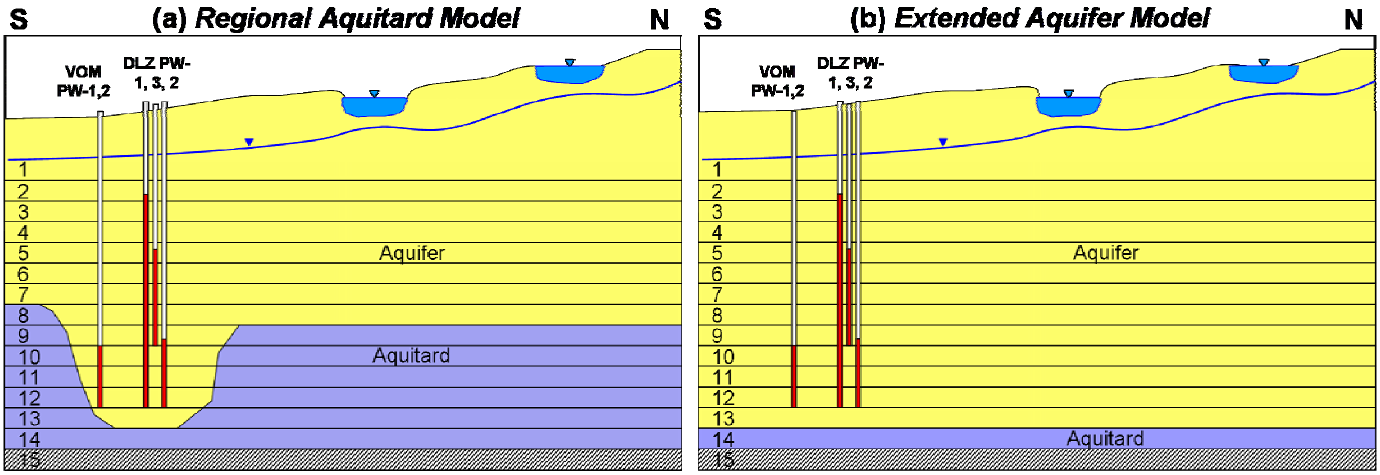

Figure 4. Two alternative conceptual end-member models for the geometry of the underlying confining unit: a) *Regional Aquitard* model, b) *Extended Aquifer* model.

In this exercise, students will be asked to predict the response of the contaminant plume migration to the onset of remedial pumping, first at the remedial pumping wells, and second at a monitoring well located between the source and pumping wells.

Part 2. Response in Pumping Wells.

***Question*: If the two conceptual models suggest different flow paths for the contaminant plumes, will these differences be detectable in the extraction wells?**

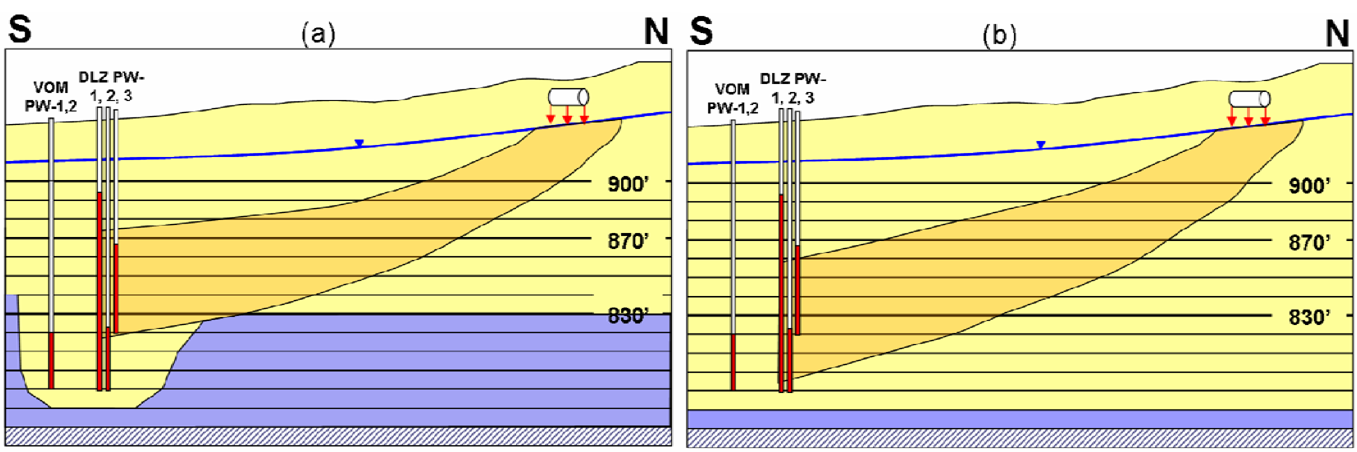

Figure 5. Postulated differences in plume pathways for the two alternative conceptual end-member models: a) *Regional Aquitard* model, b) *Extended Aquifer* model.

To answer this question, a MODFLOW groundwater flow and MT3DMS transport model were constructed. Details of the model configuration and parameters are described by Lemke and Cypher (2006). Contaminant concentration data for the pumping well effluent stream are available for 2 years after the onset of pumping in wells DLZ PW1, 2, and 3. A comparison of observed concentrations and modeled breakthrough curve behaviors is given for MTBE and cDCE in Figure 6.

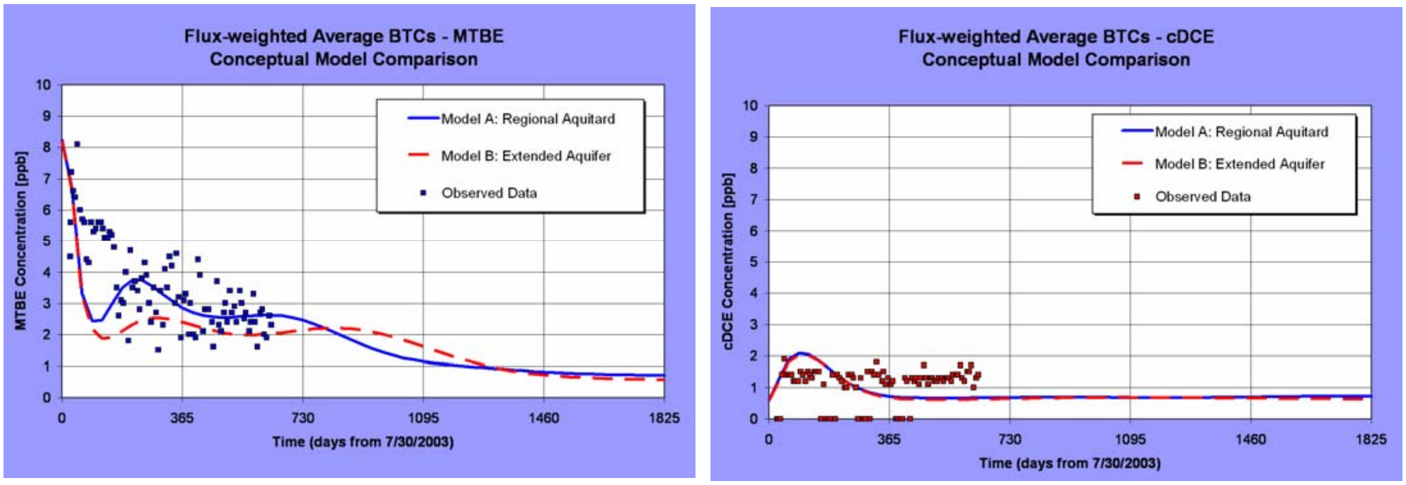

Figure 6. Observed and modeled concentrations at the extraction pumping wells: a) *MTBE*, b) *cDCE.*

Discussion Questions:

1. Why do the concentrations for MTBE decrease over time while those from cCDE remain stable? (cDCE is released from a slowly dissolving DNAPL source zone; the source of the MTBE – a leaking underground storage tank – has been removed.)

2. How well do the modeled curves fit the observed data? (Quite well – the order of magnitude agreement is within measurement variability for both compounds.)

3. Is there a meaningful difference between the two end-member model predictions? (No – both the Regional Aquitard and Extended Aquifer models match the observed curves within the range of measurement variability.)

4. Why do the predicted breakthrough curves generated using different conceptual geologic models look so similar to each other? (Because the contaminant signal is integrated across a very large screened interval that cannot distinguish between shallower and deeper pathways.)

Part 3. Response in Monitoring Wells.

Question: **Could a monitoring well detect migration of the plume in response to remedial pumping?**

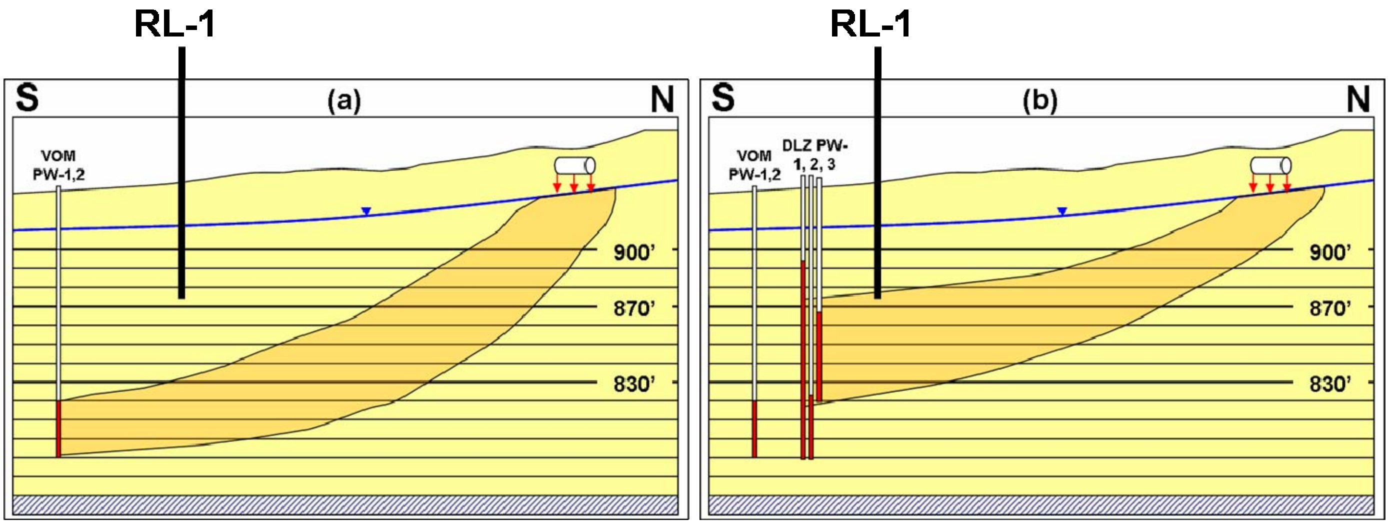

Figure 6. Postulated shift in contaminant plume position in response to remedial pumping: a) steady state condition prior to remedial pumping; b) steady state condition during continuous pumping. Note position of monitoring well RL-1, which is screened over a 4-foot interval at its base.

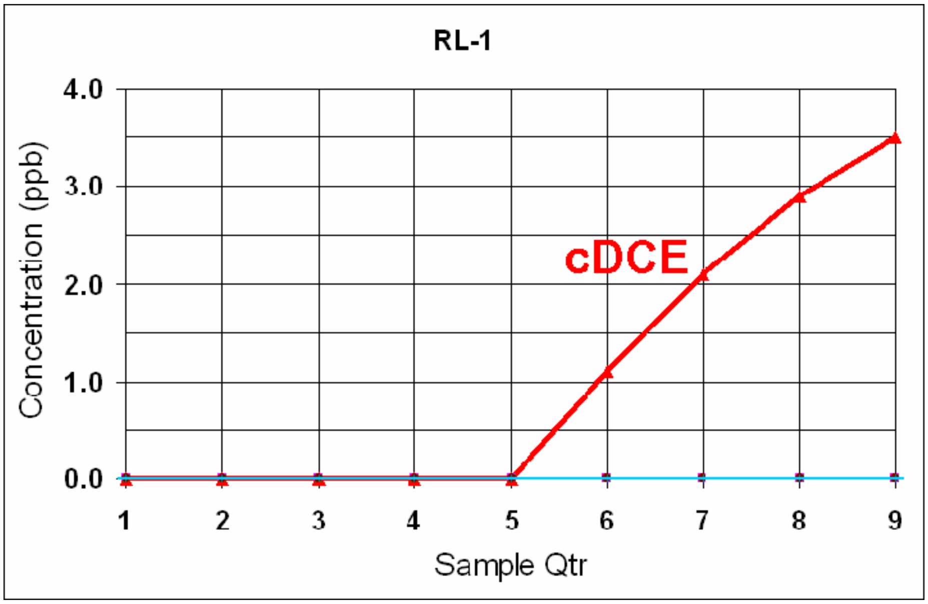

Figure 7. cDCE concentrations measured in monitoring well RL-1. Samples were taken quarterly and are plotted in quarters elapsing after the onset of remedial pumping.

Question**: Does the choice of conceptual model make any difference when trying to predict the breakthrough curve at the monitoring well?**

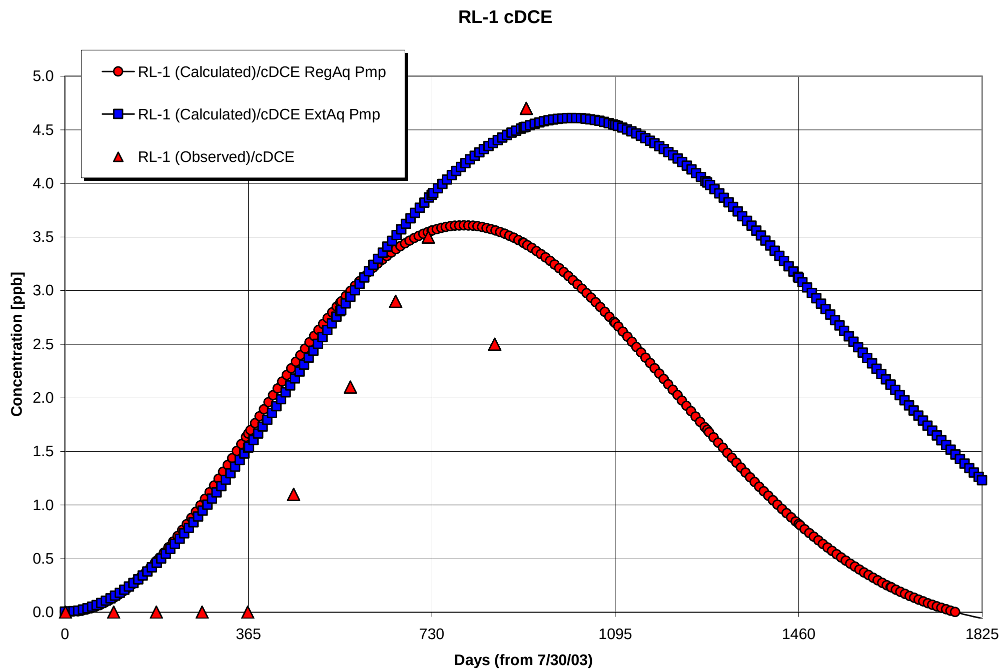

Figure 8. Measured and predicted cDCE concentrations in monitoring well RL-1.

Discussion Questions:

1. Why is the plume postulated to follow a shallower path after the onset of remedial pumping? (Because the pumping wells are screened, at least in part, across a shallower depth than the municipal water supply wells. Pumping these wells can be anticipated to drawdown the aquifer at shallower depths and change the hydraulic gradient so that the contaminant is drawn through a shallower aquifer horizon – taking a shorter path between source and sink.)

2. Why does the monitoring well show a response when the extraction wells do not? (The monitoring well is more sensitive because it only samples a 4-foot interval; hence the observed concentrations for the monitoring well are not averaged over a large vertical thickness.)

3. Do you think all monitoring wells will show a similar response? (No – the monitoring well must be in the right position vertically and horizontally to observe a change.)

4. Why does it take nearly two years before a discernable difference in cDCE concentrations is predicted for the two end-member models at RL-1? (It takes time for the flow field to re-equilibrate and it takes time for contaminants to travel from the source to the pumping wells along the new contaminant transport pathway.

5. What are the implications for monitoring well networks designed to verify the success of remedial pumping schemes? (There are many, but certainly care must be taken to locate monitoring wells in the right spots. Also, if the flow field is changed significantly, the location of the “right spots” for monitoring wells may change.)

Evaluation: Student learning can be assessed through responses given during class discussions (Are predictions reasonable? Do interpretations of the data make sense? Can alternative working hypotheses be developed?). Subsequent evaluation of concept retention can be conducted using true/false or short answer questions on subsequent quizzes or exams. Example questions:

1. State two factors that strongly influence the effectiveness of groundwater monitoring wells in detecting changes in dissolved contaminant plume migration :
   - their location (in map view and depth)
   - the screen length.

2. State two or more ways in which breakthrough curves are influenced by the design of a monitoring well:
   - the well must be screened in the right location to intercept and detect the contaminant plume.
   - the length of the screen will determine how much averaging of the contaminant concentration occurs across the vertical aquifer dimension.
   - the well screen length influences the potential dilution of samples with uncontaminated water.

3. In heterogeneous aquifers, monitoring wells screened over large intervals have a better chance of detecting the presence of contaminants than wells with shorter screened intervals. (true, provided the contaminants are not diluted below detection limits)

4. In heterogeneous aquifers, monitoring wells screened over large intervals have a better chance of detecting changes in contaminant movement in response to flow field stresses induced by remedial pumping. (false)

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