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Source area detection using groundwater model at Woburn, Massachusetts

Tanzeer Hasan
(Department of Geology, University of Dhaka, Bangladesh)

Abstract: *Groundwater contamination in the City of Woburn, Massachusetts, was first suspected when water from two municipal wells (G and H) caused illness in a number of residents. United States Environmental Protection Agency (USEPA) performed an investigation in beginning of 1979 within the Aberjona River valley. Groundwater contamination was shown to be the result of the actions of several large manufacturing and service companies located within the area. These companies often handled dangerous materials with properties that are suspected to be potential contaminant sources. The main objective of this work was to develop a conceptual model to simulate groundwater flow in the Aberjona River valley numerically. Another purpose of the study was to detect the potential sources of the contaminants in the municipal wells G and H. Using PMWIN, groundwater flow directions were simulated and PMPATH (a particle tracking model) was used to simulate contaminant transport.The simulations were run for transient state conditions under the scenario of well G and H was turned off and on, but industry well 1 and 2 were always turned on. Transient case was run for 30 days time. It is clearly seen that the model simulation for transient flow condition correctly predicts the impact of well G and H on hydraulic head contour. Contaminants travel time and pathways were calculated using PMPATH. From particle tracking, it is evident that these three properties (Unifirst, W.R. Grace and Riley) were responsible in contaminating the supply wells.Sensitivity analysis is performed on transient flow conditions to observe the changes in hydraulic heads. It is observed that the model is least sensitive to variations in porosity, and most sensitive to variations in recharge, order-of-magnitude changes in riverbed conductance and pumping rates.*

Keywords: *Contaminant Transport, Groundwater Modeling, MODFLOW,PMWIN, PMPATH*

I. Introduction

The In the City of Woburn, within the Aberjona River valley, Massachusetts Department of Environmental Quality Engineering (MDEQE) identified different contaminants in two public supply wells G and H on May 1979 after causing illness in a number of East Woburn's residents. Due to a number of industrial and manufacturing companies located in this zone, groundwater was contaminated. These companies often handled dangerous materials with properties that are suspected to be potential contaminant sources (Myette et al., 1987). Figure 1 shows an aerial photograph of the site of interest at the time of the USEPA investigation. It can be clearly understood that the Aberjona River meanders through the valley. On the eastern side of the river, there were well G and well H next to a wetland and on the western side there were two tannery wells and the positions of the different companies are indicated in the Figure 1. Beatrice Foods, owner of the former John J. Riley Leather Corporation, is located at the corner of Wildwood Avenue and Salem Street. On Washington Street, a food processing equipment manufacturer W.R. Grace & Corporation, is located. An industrial dry-cleaning plant, UniFirst Corporation is located on Olympia Avenue. The 15-acre Riley property of Wildwood Conservation Corporation, Olympia Nominee Trust and New England Plastics are also situated in the surrounding region of Woburn, Massachusetts. Between 1985 and 1988, the US Geological Survey (USGS) provided technical assistance to US Environmental Protection Agency (USEPA), including measurements of streamflow, surface-geophysical surveys, design and supervision of a 30-days aquifer test and analysis of aquifer test data, at the wells G and H site (Myette et al., 1987).

TCE, which is a well-known trade solvent specifically in grease and oil industries, were responsible for well H and G contamination in Woburn. Other contaminants like tetrachloroethelyne, were also present in those wells (Harr J., 1995). Six contaminants of concern ranging in concentrations of 1 to 400 parts per billion were identified in the water by the Massachusetts Department of Environmental Quality Engineering (MSEQE) and noted in a report issued by the United States Geological Survey (Myette et al., 1987). The traced contaminants were- (a)Tricholoroethene (Trichloroethylene, TCE); (b) Tetrachloroethylene (PCE, perc); (c) Trichlorotrifluoroethane (CFC-113); (d) 1,2-Transdichlorethylene (1,2,-DCE); (e) 1,1,1-Trichloroethane (1,1,1-TCA), and(f) Chloroform.Five companies- W.R. Grace, UniFirst Corporation, Wildwood Conservation Corporation, Olympia Nominee Trust, and New England Plastics Corporation around the Woburn area were identified as potential sources of the contaminants mentioned above (Bair and Metheny, 2002). In Figure 1 the position of the five companies who were responsible for the groundwater contamination along with the Wells G and H and river has been shown *(*Lahm, *NSF)*. TCE, 1,2-DCE and Vinyl chloride was found in the *W. R. Grace property*. The highest concentrations found were 8000 µg/L of TCE and 12000 µg/L of 1,2-DCE (Bair and Metheny, 2002). Because of the improper management facilities, these toxic compounds pierced into groundwater. Dry-cleaning industry the *UniFirst* released 2200 to 17000 µg/L concentrated PCE in the late 1980s and smaller amounts of TCE, 1,2-DCE, and 1,1,1-TCA (Bair and Metheny, 2002). The Wildwood Conservation Corporation dumped various wastes illegally and the investigated committee identified very high levels of TCE in the soil (greater than 830 000 mg/kg) and the groundwater (greater than 440 000 µg/L) near a former debris pile (Bair and Metheny, 2002).

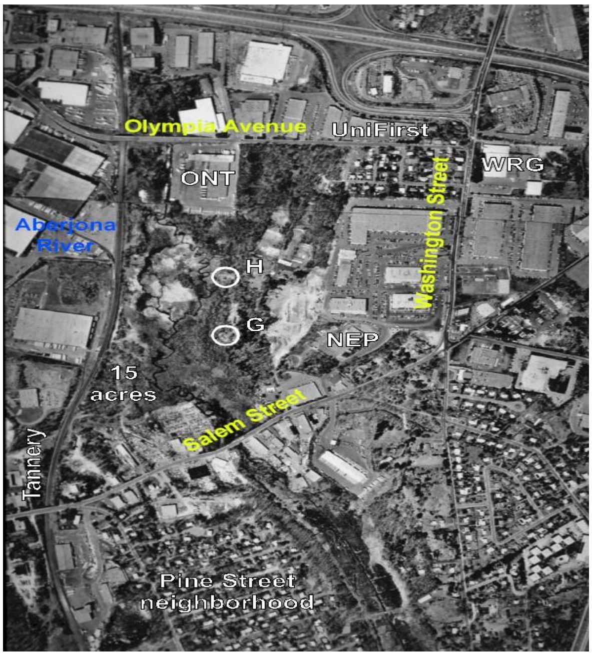

Figure 1: Aerial photograph of Aberjona River valley and Wells G & H with defendants.

While predicting contaminant transport through the model in Woburn area, there would be some uncertainties that should be mentioned. While considering modeling parameters, we assumed homogenous soil properties. But in real case, the subsurface was heterogeneous. In different spaces of the subsurface, geologic and hydrologic conditions were varying. The aquifer was composed of different soil types and different soil types have different properties. So it is not logical to assign same hydraulic conductivity for the stratified drift aquifer. Furthermore, the variable geology of the site made modeling more complicated. For example, a steep hill slope east of wells G and H shows the location of a steep, west facing, near surface bedrock boundary. This boundary causes drawdown to be small east of the wells while drawdown between the wells is increased (Myette et al., 1987). There were hydraulic connection between the Aberjona River and the well G and H, which is the cause of uncertainty as well. Generally, the aquifer surrounding the wells supplied water to them. So here contaminant will be transported through the subsurface with flowing groundwater towards the bedrock depressions near wells G and H. The presence of the Aberjona River would cause induced infiltration of surface from the overlying river and wetland areas when wells G and H are pumped heavily (Myette et al., 1987). Therefore, it would be difficult to realise the actual reason for the contamination in the wells, i.e., whether the contamination is due to the contaminated sources in the upstream of the river or due to the disposal of contaminant in Woburn areas.

II. Geology and Hydrogeology of the Woburn site

2.1Geological settings

Two types of principal geologic formations were there in Woburn site glacial deposits of gravel, sand, silt and clay and igneous bedrock. In Figure 2, a geologic cross-section from southwest to northeast has been shown. It was extended from Beatrice property, through well G to the W.R. Grace property. In this Figure 2demonstrated the shape of the bedrock surface and subsurface lithology. A discontinuous layer of highly compacted sediments occurs along the bottom and the margins of the bedrock valley *(*Metheny, *1998)*. The surrounding areas of the two wells were composed of heterogeneous and discontinuous layers of glacial river deposits, glacial lake deposits, and modern fluvial and wetland deposits. There were different amount of fracturing in the bedrock. There were sloping east and west walls in the valley.

2.2 Hydrogeology

The groundwater in the stratified drift area was generally unconfined (Fig. 3). In the aquifer, water levels varied continuously along with variation in discharge and recharge. The aquifer was recharged through precipitation and groundwater flow from upland areas lying east and west of the valley. Bedrock in the area is known to yield small quantities of water to pumped wells *(*Gay F. B et al., *1980)*. The igneous bedrock beneath the site represents a confined aquifer and is sufficiently permeable to yield moderate groundwater flow (NUS, *1986)*. Wells G and H were located within the stratified drift below the rivers lowlands, and the estimated transmissivity of these deposits was in excess of 370 m^2/d. Higher transmissivities were estimated in the areas directly around the two wells.

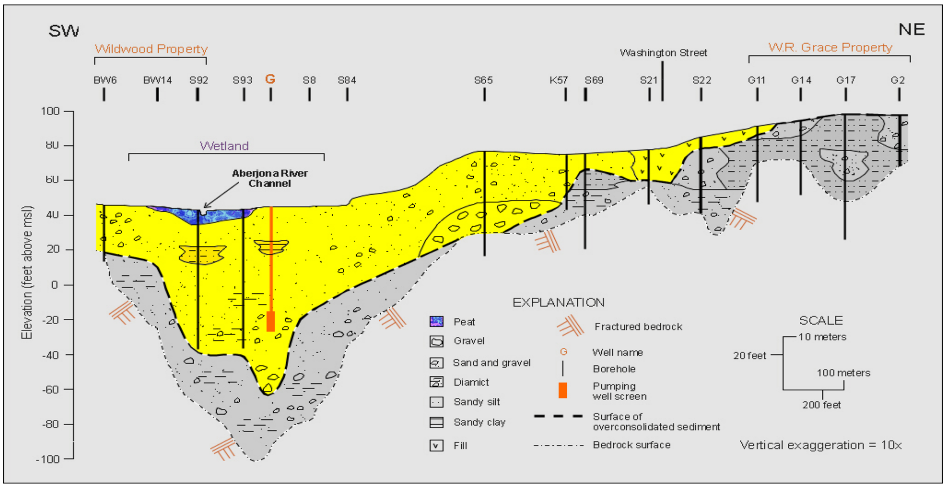

Figure 2: Cross section illustrating buried bedrock valley with glacial fill *(*Metheny, *1998)*.

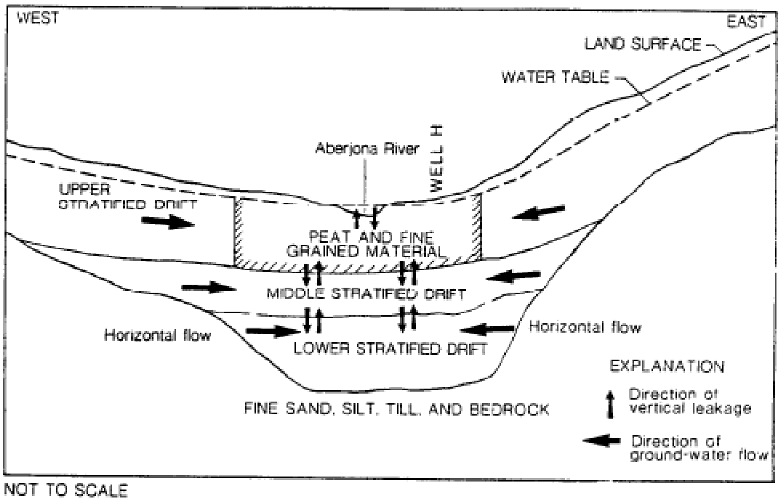

Figure 3: Generalised cross-section of the Woburn Site *(de Lima and Olimpio, 1989)*

Under pumping conditions, groundwater was recharged partly to the wetland and river and partly to pumped wells. Under non-pumping conditions, the groundwater discharged to the river and wetland areas, where the two wells were located. A 30-day aquifer test was carried out at the site and described by Myette et al. (1987). In Figure 4, a map of the water table with pumping from wells G and H has been shown. It also shows that the gradient across the wetland area to be gentle. The water table was often at or near the surface in the low-lying areas and 3 to 4.5 meters below the surface in the upland areas. It was evident that the groundwater flows from high elevations on the eastern and western bedrock walls to the lower elevations of the bedrock valley. The vertical hydraulic-head gradients on the western side are generally smaller than those on the eastern side. The permeabilities of the major stratigraphic layers at the Woburn Site are as follows (Myette et al., 1987): Igneous bedrock – very fractured and highly connected, lower glacial deposits layer of coarse sand and gravel – high permeability, intermediate layer of fine to coarse sands – medium to high permeability and top layer of sand, silt, clay and peat – medium permeability.

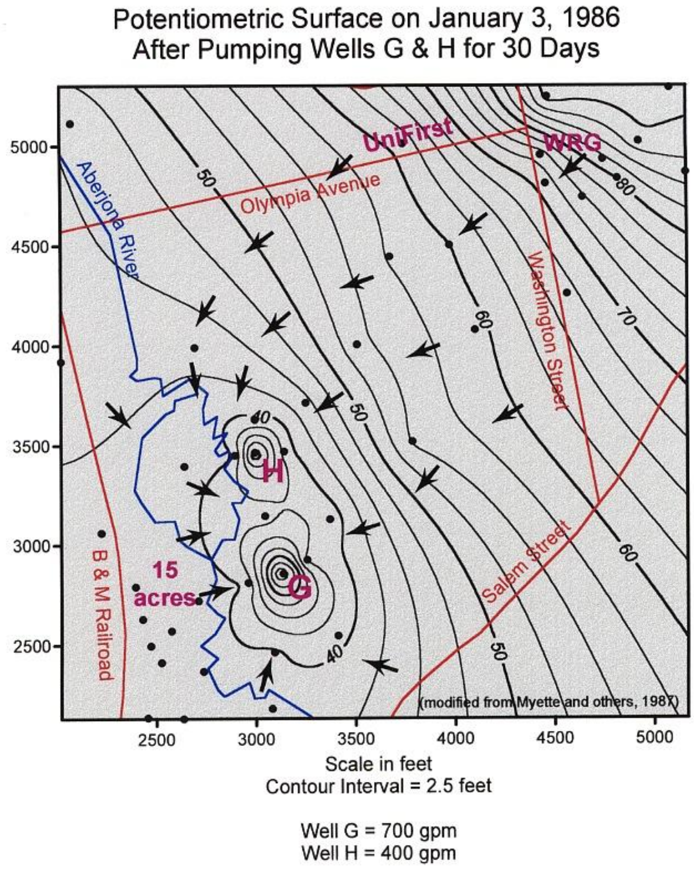

Figure 4: Water table map after 30 days of pumpage from the two wells *(*Myette et al., *1987)*

III. Methodology

3.1 Modeling approaches

Processing Modflow for Windows (PMWIN) is a graphical interface for MODFLOW that integrates MODFLOW with various packages that simulate a specific feature of a hydrologic system. These packages include an advective transport model (PMPATH), solute transport models (e.g., MT3D and MOC3D) and parameter estimation programs (e.g., PEST) that combine with MODFLOW to create a system capable of simulating groundwater flow and transport processes (Chiang and Kinzelbach, 1998). To model the aquifers within the Aberjona River and within the areas surrounding wells G and H, PMWIN was used.

3.2 Grid

Aberjona River valley has been overlaid on a rectangular map of the site with approximate area of 0.8 sq. mile. The spacing of the different grids was variable to specify the area of interesting parts of the site. The coordinate system was rotated to allow for the grid to be aligned parallel to the river. The model cells ranged from 20 x 20 ft to 200 x 200 ftand consisted of nearly 5000 active nodes in 3 model Layers (de Lima and Olimpio, 1989). Because of narrowing bedrock valley, the boundaries of Layer 2 and Layer 3 were narrower than Layer 1 in the model grid. Figure 5 represents the grid spacing of model at left and according to the USGS at right for Layer 1.

3.3 Assumptions

The following assumptions were taken based on de Lima and Olimpio, 1989 are given below *(*de Lima and Olimpio, 1989*)*:

1. Horizontal flow only:

To simulate the flow condition in the model, it is assumed that horizontal flow occurs within each layer and one-dimensional vertical flow occurs between the layers. The vertical flow appears only while pumping wells.

2. No leakage from till and bedrock:

Till and bedrock are set as no-flow boundaries, with no leakage occurring. Although leakage from till and bedrock is suggested by the horizontal and vertical head gradients in the study area *(*Myette et al., *1987)*, because of data limitations this criteria is excluded from the modeling.

3. No-flow into or out of the site:

Northern and southern boundaries are set to no-flow boundaries though there is a little chance of groundwater flow occurring across the boundaries.

4. Uniform properties of peat and streambed deposits:

It is assumed single vertical hydraulic conductivity for all layers of the Model but horizontal conductivity has been used from the default model values for each layers (river, and peaks also) to simplify the complexity.

5. Efficient and fully screened pumping well:

In real case, it is not possible for a well to pump with 100% efficiency and fully screened in all layers. But in Modeling it is assumed that the case is 100% efficient and fully screened.

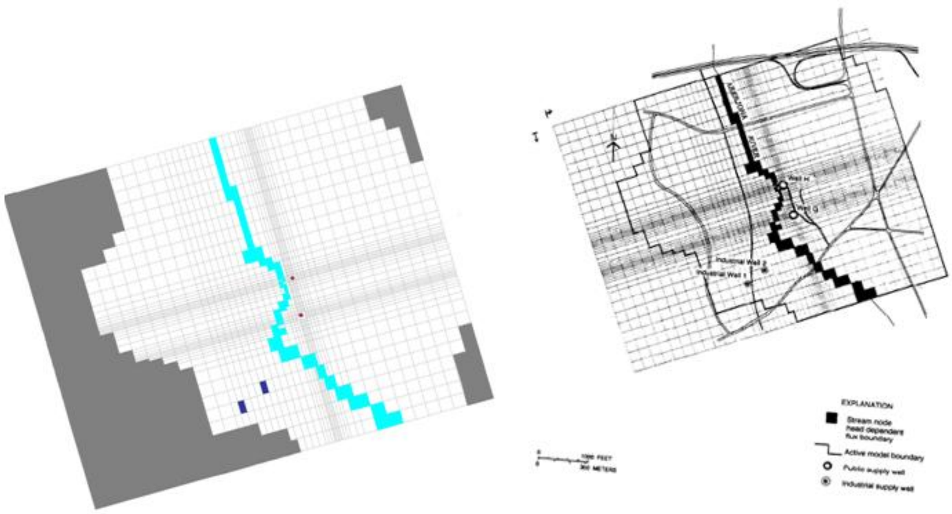

Figure 5: Groundwater Grid for the Aberjona River Valley in vicinity of Well H and G, Woburn, Massachusetts: Model (Left), USGS (Right)

3.4 Layers

In MODFLOW, PMWIN has four types of layer:

- **i.** *Type 0*: A strictly confined layer.
- **ii.** *Type 1*: A strictly unconfined Layer.
- **iii.** *Type 2*: A layer between confined and unconfined with constant tansmissivity.
- **iv.** *Type 3*: A layer between confined and unconfined with varying tansmissivity.

In this simulation, for transient flow condition, simulation was done considering type 1, 3 and 0 for three stratigraphic layers.

Table 1: Different parameters of Layer 1, 2, and 3

Parameters / *Layer*	*1*	*2*	*3*
Type	Sand, Silt, Clay	Fine to coarse sand	Thick coarse sand and gravel deposits
Thickness	20 - 30 ft	30 ft	10 - 50 ft
Porosity	0.25	0.25	0.25

The values of different parameters are shown in Table 1 for modelling which has been obtained from the USGS report. According to the report, screen of industrial well 1 and 2 was situated in Layer 2 and 3 respectively. Besides, Well H and G were screened in Layer 3 *(*de Lima and Olimpio,1989*).*

3.5 Boundary conditions

The no-flow conditions on the eastern and western sides represented the natural till and bedrock boundaries of aquifer. East and west boundaries narrowed through the underlying layers to coincide with the sloping sides of the bedrock valley. The northern and southern boundaries were also set to no-flow conditions, meaning that groundwater could not flow into the northern boundary or out of the southern boundary. The Aberjona River was simulated as a head-dependant flux boundary, with the hydraulic head computed during the simulation(de Lima and Olimpio,1989*).*

3.6 Borehole positions

Twenty bore-holes were selected from the USGS study and their locations were identified on the model grid. No-flow boundaries were assigned to all sides of the model grid for all three layers. For simulation, the Aberjona River was considered as head-dependant flux boundaries, with the hydraulic head computed during the simulation. The simulated head values for the aquifer were compared with observed values of the bore-holes obtained from the USGS study.

3.7 Modeling scenario

3.7.1 Transient flow condition

For Transient flow condition, storage coefficients and specific yields were obtained from the USGS report and used in Modeling in addition to the steady state flow condition parameters. Specific yield is a parameter for unconfined aquifer and storage coefficient for confined aquifer condition. In Table 2, these dimensionless parameters have been mentioned. The value of the storage coefficient was 0.0005 determined by the 30-day pump test of the USGS modeling study *(*de Lima and Olimpio*, 1989).* For Transient flow simulation, Wells G and H were turned on.

Table 2: Parameters for Transient Flow Modelling.

Parameters		*Values*
Specific Yield	Peat (surrounding area of river)	0.45
	Rest of part of Layer 1	0.30
Storage Coefficient	Layer 2	0.0005
	Layer 3	0.0005
Time		30 days

3.7.2 Particles Tracking

The particle tracking model PMPATH uses a semi-analytical particle tracking scheme to calculate the groundwater paths and travel times. Both forward and backward particle tracking schemes are allowed for transient flow field.The PMPATH was used to determine travel times of contaminants from the source locations to the municipal Wells G and H.

IV. Results and Discussions

1.1 Transient flow conditions

To simulate the transient condition, some modifications were made and some new model input data were considered. The well G and H were considered to be at pumping condition from December 4, 1985 to January 3, 1986. It means the transient model was simulated for 30 days. The pumping rate of well G and H were 700gal/min and 400gal/min respectively as described by the USGS (de Lima and Olimpio, 1989). Moreover, storage coefficients, specific yield and vertical hydraulic conductivity were considered in transient model simulation to resemble actual pumping conditions within the Aberjona River valley.

The following Figures 6 and 7 show the comparison of contours of hydraulic head for Layers 1 and 3, respectively, under transient flow condition with USGS head contours after 30 days of well pumping. Similar to USGS report, cones of depression in hydraulic heads are evident in the vicinity of the municipal wells G and H, and as well as in the vicinity of the industrial wells 1 and 2 in model simulation. Comparing with the steady state condition, it is clearly seen that the model simulation for transient flow condition correctly predicts the impact of well G and H on hydraulic head contour.

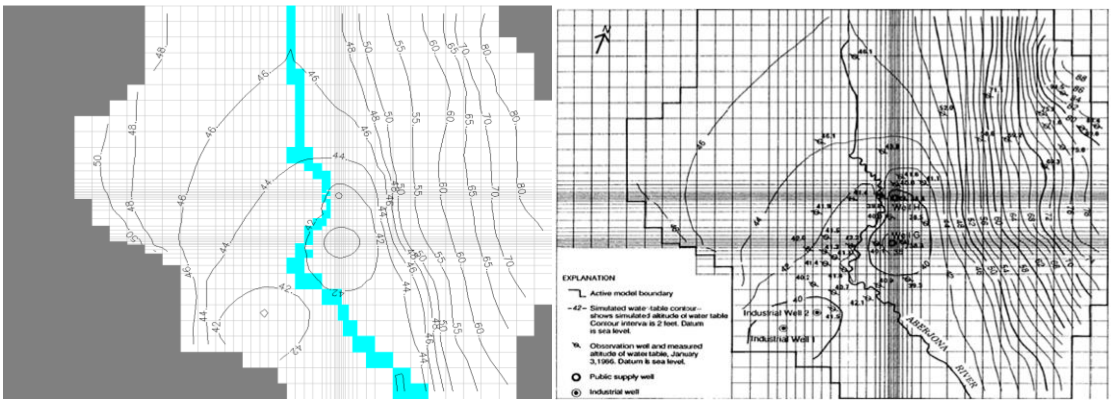

Figure 6: Contour plots for (Left) MODFLOW simulated heads, and (Right) USGS simulated heads of Layer-1 for Transient flow condition.

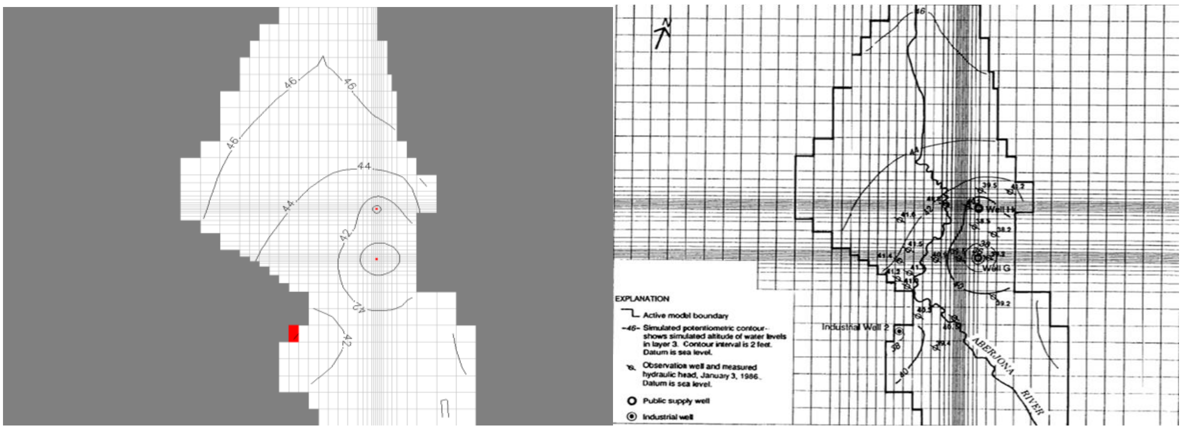

Figure 7: Contour plots for (Left) MODFLOW simulated heads, and (Right) USGS simulated heads of Layer-3 for Transient flow condition.

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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    1

===============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
===============================================================

       FLOW TERM           IN             OUT           IN-OUT
         STORAGE   2.1376379E+00  2.8597492E-01  1.8516629E+00
   CONSTANT HEAD   0.0000000E+00  0.0000000E+00  0.0000000E+00
           WELLS   0.0000000E+00  3.0900002E+00 -3.0900002E+00
          DRAINS   0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE   1.1696182E+00  0.0000000E+00  1.1696182E+00
              ET   0.0000000E+00  0.0000000E+00  0.0000000E+00
   RIVER LEAKAGE   8.4370875E-01  7.8081620E-01  6.2892556E-02
 HEAD DEP BOUNDS   0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE   0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE   0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE   0.0000000E+00  0.0000000E+00  0.0000000E+00
---------------------------------------------------------------
             SUM   4.1509647E+00  4.1567912E+00 -5.8264732E-03
 DISCREPANCY [%]  -0.14
```

Figure 8: Water budget after 30 days for Transient flow condition after pumping from well G and H.

Figure 8 shows the water budget of the entire model area after 30days pumping. The total amount of water that is coming out from groundwater system (OUT) is a sum of storage, well pumping, and river leakage. From model simulation, water budget calculation shows that approximately 4.157 ft^3/sec water has been removed from the groundwater system for transient flow condition. Because of river leakage, approximately 0.781ft^3/sec water was removed from the system while 3.09 ft^3/sec water was coming out due to pumping of well G and H in addition tannery well 1 and 2. The quantity of water volume that came out due to storage was 0.286 ft^3/sec. On the other hand, the amount of water that entered into the groundwater system was 4.151 ft^3/sec, which was the combination of storage, recharge and river leakage.

4.2 Sensitivity analysis

This analysis was conducted to observe the effect of case (layer 1-Unconfined, layer 2-Confined/Unconfined- transmissivity (constant) and layer 3-Confined) and pumping rate of well H, recharge and the Riverbed conductance. The simulated hydraulic head and 15% increase at pumping rate of well H are compared with the measured head at observation wells(Fig. 9). The corresponding contour plots are shown in Figure 10.

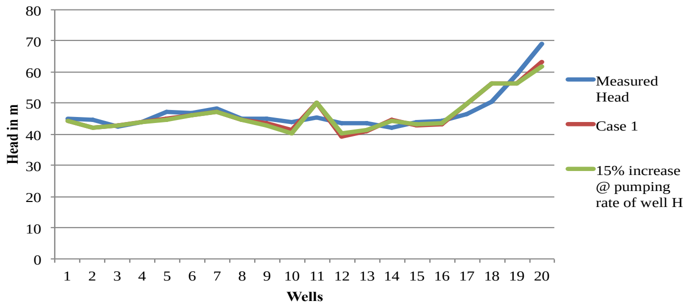

Figure 9: Simulated heads with for Case I and 15% increase at pumping rate of well H.

The default value for the pumping rate of well H was 0.89 ft^3/sec in the model. We increase the pumping rate 15% for this case and run the simulation to observe the change in head. We found there is a negligible change in the hydraulic heads of the groundwater due to the variation of the pumping rate of the well H.

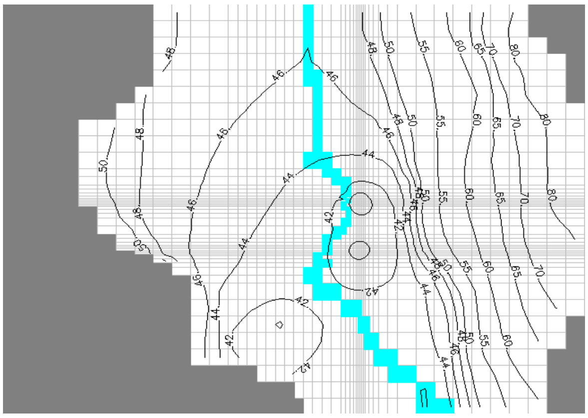

Figure 10: Simulated heads at the end of 30-day test in Layer 1 for transient Conditions with 15% increase at pumping rate of well H.

4.2.1 ***Impact of River conductance***

To observe the impact of riverbed conductance on hydraulic head in the transient condition, several simulations were done. First, we took the model default values then we increase and decrease the value 10 times from the model values and we also run simulation without riverbed conductance. For this purpose three cases were simulated.

Case I: Model default value of riverbed conductance multiplied by 10.

Case II: Model default value of riverbed conductance divided by 10.

Case III: Without conductance.

The hydraulic head contours for all the above three cases are given in Figures 11 and 12 respectively for layer 1. The resulting simulated hydraulic heads at each observation well are tabulated in Figure 13 for the layer I.

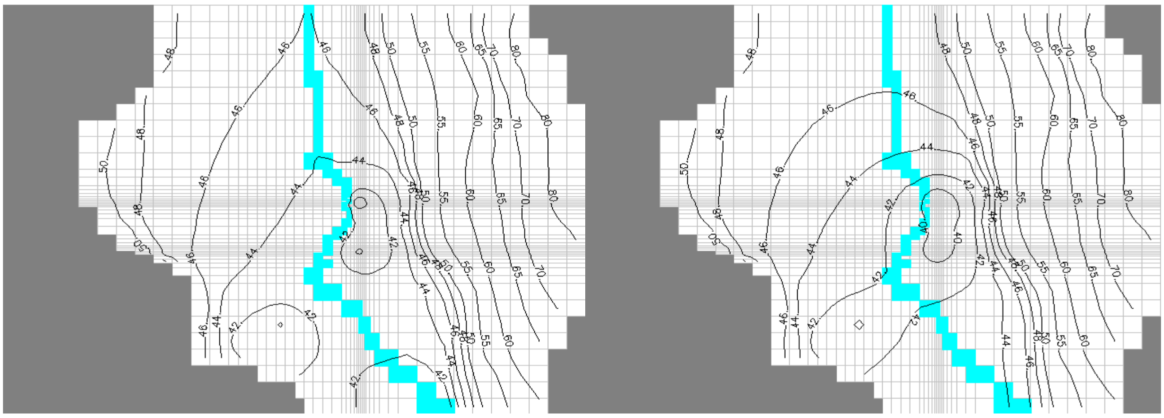

Figure 11: Simulated heads at the end of 30-day test in Layer 1 for Transient Conditions with 10 times (Left) river conductance and 1/10 times river conductance (Right).

It is observed that simulated head for no hydraulic conductivity and hydraulic conductivity decreased by one order magnitude have almost same values. This is because of very low conductivity for the case I. Simulated head increases when hydraulic conductivity increased by one order magnitude, on the other hand it decreases hydraulic conductivity decreased by one order magnitude.

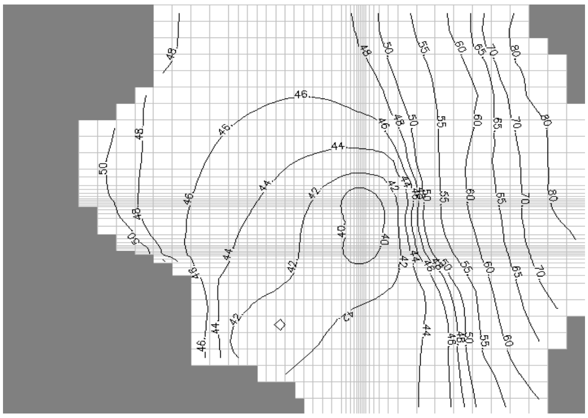

Figure 12: Simulated heads at the end of 30-day test in Layer 1 for Transient Conditions without river conductance.

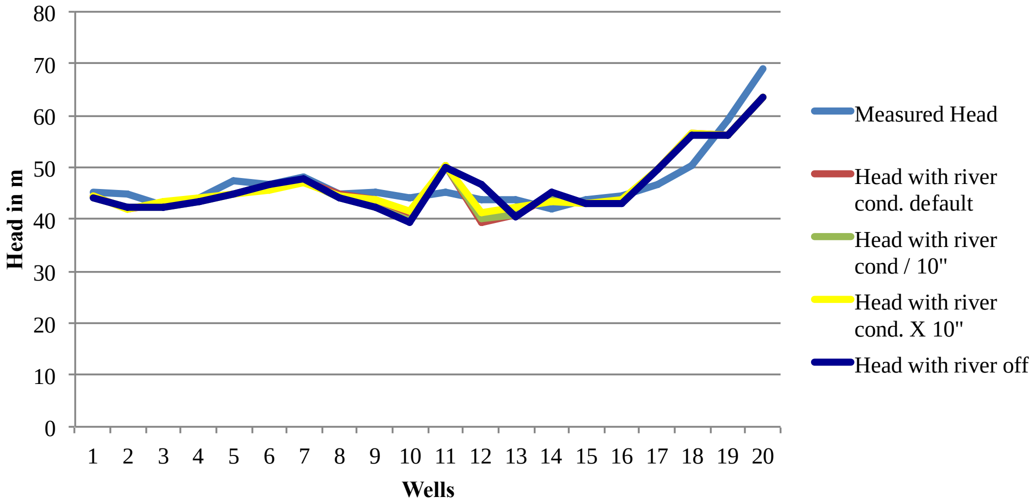

Figure 13: Simulated heads with variations in riverbed conductance (Transient).

4.2.2*Recharge*

The model value for the recharge was 20 inches per years (i.e., 5.29 x 10^{-8}) for transient case. We change the recharge into 10 and 30 inches per year to conduct the sensitivity analysis. The measured and simulated heads for both rates of recharge were obtained at each observation well and tabulated (Fig. 14).

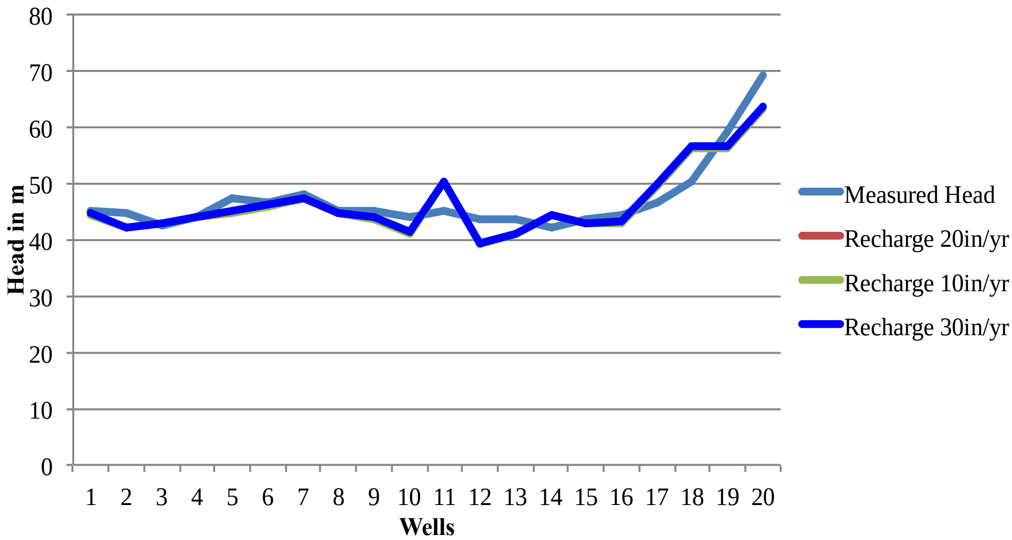

Figure 14: Hydraulic head values for simulated test cases and observed/measured values (Transient).

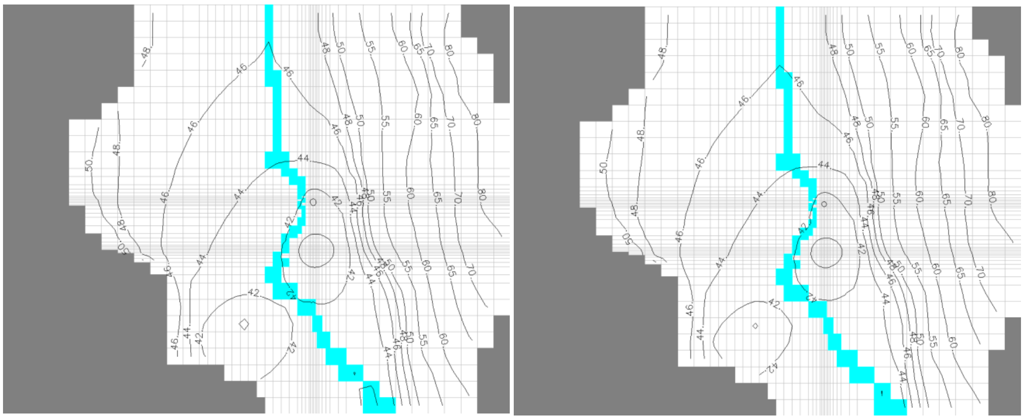

Figure 15: Simulated heads at the end of 30-day test in Layer 1 for steady state conditions with recharge of 10 and 30 inches per year respectively for the transient case.

It was observed that water level drop during lower recharge and rose during the higher value of recharge. The corresponding contour plots for both recharge rates are shown in Figure 15. As expected, it is evident from the Figures that the hydraulic heads have decreased due to a reduction in the rate of recharge.

4.3 Particle tracking

Using PMPATH, travel time of contaminants from the source locations to the municipal Wells G and H were determined. The particles were entered on the top layer of the cell block in layer one. So, the particles were placed on top of the surface (on the top face of a cell). The step forward function of PMPATH was used to determine the time at which the contaminants reach the municipal supply wells. One-year time step was used. The particle tracking was simulated using flow lines. The results for the different travel times from each of the three properties are tabulated in Table 10.

4.3.1 Effects of Retardation Coefficient

For sensitivity analysis of the particle tracking times, different values of retardation coefficients were used. For the chlorinated solvents in sand and gravels, retardation coefficient typically ranges from 1 to 10. In this analysis, 1, 3 and 6 were used as retardation coefficients. Sorption was represented by the retardation coefficient, which typically ranges from 1 to 6. Retardation factor is used to determine the ratio between contaminant velocity and groundwater velocity. For W.R Grace, when the retardation coefficient is increased from 1 to 3, the travel time increases from 7 years to 19 years. When stepping forward through the particle paths, same results were obtained from the plots with varying retardation coefficients. The only variation was the amount of time steps required before the contaminant reached either Well G or Well H or both. It means that while the contaminant were moving forward they took the same contaminant pathways; however the velocity of the contaminant were changed with varying R values.

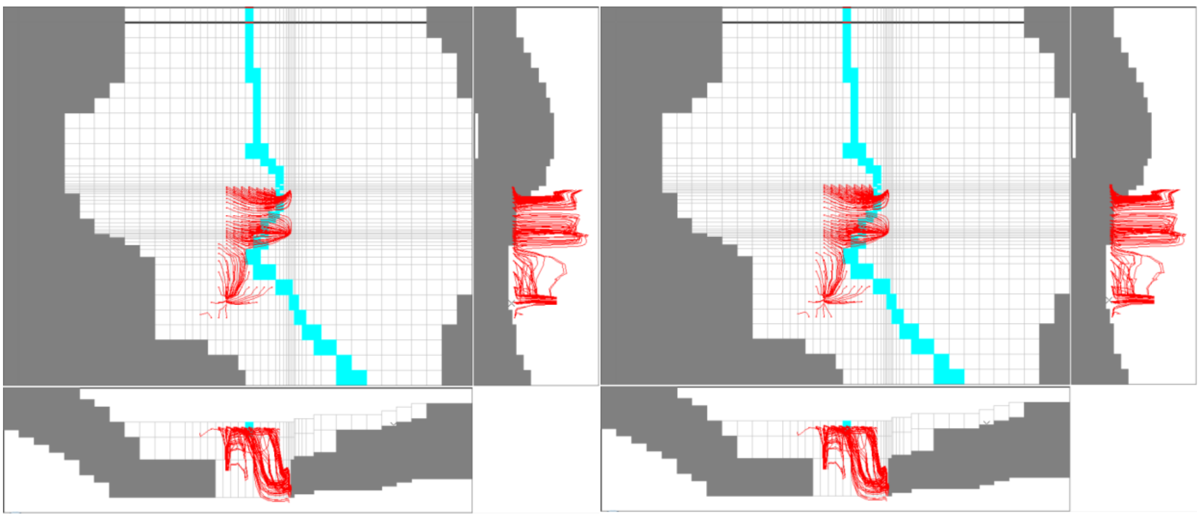

Figure 16: Particle tracking (above is the plane view and below is the cross-sectional view) from Riley to the wells G and H (R=1 for Left; R=6 for Right).

Table 3: Travel times from Unifirst, W.R. Grace, and Riley to Wells G and H.

Ccompanies	Particles Per Cell	R	River	G & H Pumping Rates	Hydraulic Conductivity (V)	Travel Time to Well H (years)	Travel Time to Well G (years)
Unifirst	3x3	1	Default	Default	Default (.00001)	5	-
	3x3	3	Default	Default	Default	14	-
	3x3	6	Default	Default	Default	30	-
	3x3	1	River Cond Div by 10	Default	Default	4	-
	3x3	3	River Cond Div by 10	Default	Default	10	-
	3x3	6	River Cond Div by 10	Default	Default	21	-
	3x3	1	Default	Default	0.0002	4	-
	3x3	3	Default	Default	0.0002	13	-
	3x3	6	Default	Default	0.0002	28	-
	3x3	1	Default	Pumping Rate decrease 50%	Default	8	-
	3x3	3	Default	Pumping Rate decrease 50%	Default	23	-
	3x3	6	Default	Pumping Rate decrease 50%	Default	47	
W.R. Grace	3x3	1	Default	Default	Default	7	-
	3x3	3	Default	Default	Default	19	-
	3x3	6	Default	Default	Default	44	-
	3x3	1	River Cond Div by 10	Default	Default	6	-
	3x3	3	River Cond Div by 10	Default	Default	18	-
	3x3	6	River Cond Div by 10	Default	Default	35	-
	3x3	1	Default	Default	0.0002	8	-
	3x3	3	Default	Default	0.0002	19	-
	3x3	6	Default	Default	0.0002	44	-
	3x3	1	Default	Pumping Rate decrease 50%	Default	8	-
	3x3	3	Default	Pumping Rate decrease 50%	Default	26	-
	3x3	6	Default	Pumping Rate decrease 50%	Default	49	-
Riley	1x1	1	Default	Default	Default	1	2
	1x1	3	Default	Default	Default	2	6
	1x1	6	Default	Default	Default	4	11
	1x1	1	River Cond Div by 10	Default	Default	1	2
	1x1	3	River Cond Div by 10	Default	Default	3	5
	1x1	6	River Cond Div by 10	Default	Default	5	10
	1x1	1	Default	Default	0.0002	1	2
	1x1	3	Default	Default	0.0002	2	6
	1x1	6	Default	Default	0.0002	4	10
	1x1	1	Default	Pumping Rate decrease 50%	Default	1	3
	1x1	3	Default	Pumping Rate decrease 50%	Default	3	10
	1x1	6	Default	Pumping Rate decrease 50%	Default	7	22

It is observed from the above plots (Fig. 16) that from Riley the contaminant travelled to both the wells G and H. The contaminants reached earlier in well H than in well G. For retardation coefficient, R=1, the contaminant reached to well H at 1 year and to well G at 2 years. With increasing retardation coefficient, the travel time for the contaminant to both the wells were increased. For R=3, it took 2 years for the contaminant to reach to well H and 6 years to well H and for R=6, the times were 4 years and 11 years respectively.

4.3.2 Effect of Riverbed Conductance

To consider the effect of riverbed conductance on the contaminant travel time, different cases were considered: (1) the default river values (original input into the model) and (2) default value of riverbed conductance/10. When the riverbed conductance was reduced, the travel time of contaminants for Unifirst and W.R Grace were decreased as well. However, for Riley it showed no effect for R=1. For R=3 and R=6 (Case (2)), travel time was increased for well H but decreased for well G. This change did not seem to be that much significant when it is compared to the travel time differences observed from varying the retardation coefficients. So effect of riverbed conductance was not that much important.

4.3.3 Effect of Vertical Hydraulic Conductivity

For both Unifirst and Riley, when vertical hydraulic conductivity was increased, the travel time was decreased. That means increased hydraulic conductivity caused the particles to travel faster through the subsurface. However, for Grace there were little or no effects of vertical hydraulic conductivity in the travel time of the contaminants.

4.3.4 Effect of Pumping Rates

Sensitivity analysis was also conducted by changing the pumping rates of the wells and the travel times were simulated. The initial pumping rates were the rates obtained from the USGS study - 700 gal/min (Well G) and 400 gal/min (Well H). The simulations involved only a decrease in the pumping rates. The pumping rates were not being increased for analysis, as the wells will not be able to pump beyond their 100% efficiency. The pumping rate of municipal supply wells G and H were decreased 50% and the travel times of the contaminant were increased in all three properties except only for Riley at R=1.

4.3.5 Potential Contamination of Groundwater by Unifirst, W.R. Grace and Riley

For the Unifirst property, the contaminants did not reach well G as well H intercepted it. The shortest travel time for Unifirst was found to be 4 years for a retardation coefficient of 1 and riverbed conductance/10. Also, Contamination from W.R. Grace's property was interrupted by well H and did not reach well G. While being transported, contaminants would go through sorption; a higher R-value would be more logical. The travel times of contaminants at Riley properties were relatively short. If this land were contaminated, the chemicals would quickly be transported to both the wells G and H. The range of particle tracking times for well H from the Unifirst property is from 5 years to 47 years, from the W.R.Grace property is from 6 years to 49 years and from the Riley property is from 1 year to 7 years. Therefore, the contaminants migrated from the Riley property and reached well H many years earlier than the other two properties.

V. Conclusion

For transient state sensitivity analysis, the hydraulic heads have decreased due to a reduction in the rate of recharge. It was observed that water level drop during lower recharge and rose during the higher value of recharge. We found there is a negligible change in the hydraulic heads of the groundwater due to the variation of the pumping rate of the well H. After simulating the groundwater flow directions, contaminants travel time and pathways were calculated using PMPATH. From particle tracking, it was evident that these three properties were responsible in contaminating the supply wells. The Unifirst and W.R. Grace were responsible for contaminating well H only. The contaminants from these two properties did not reach well G. However, Riley property was responsible for contaminating both the wells. And from Riley property, the contaminants were reaching the wells in shorter time intervals. From sensitivity analysis, it was evident that while the contaminant were moving forward, they took the same contaminant pathways; however the velocity of the contaminant were changed with varying R values. So increasing sorption would cause a decrease in the travel time and vice-versa. Increased hydraulic conductivity caused the particles to travel faster through the subsurface in most cases. When the pumping rates were decreased, the travel times of the contaminant were increased in all three properties. From this analysis using PMWIN and PMPATH, the Woburn contamination was being understood clearly. The numerical model showed the groundwater flow directions and contaminant travel pathways and times for predicting the origin of contaminants within the Aberjona River valley.

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