

HYDROGEOLOGIC INVESTIGATION OF VOC CONTAMINATION IN BEDROCK USING MASS FLUX ANALYSIS – A CASE HISTORY

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Abstract

A fractured bedrock system was investigated using a combination of hydrogeologic methods to minimize the number and depth of bedrock wells installed during the investigation. These methods were used to determine the vertical and horizontal extent of volatile organic compounds (VOCs) in groundwater. Mass-flux analysis proved to be extremely useful in determining the vertical extent of VOC contributions to the groundwater-flow system.

The Site is located near a groundwater divide within the wellhead protection areas of two public drinking-water supplies. VOCs (primarily tetrachloroethene, chlorobenzene, dichlorobenzene isomers, trichlorobenzene isomers, and trichloroethene), were released directly to the fractured bedrock through a catch-basin structure installed within the shallow bedrock. No evidence of DNAPLs was found, but a strong downward hydraulic gradient observed in relatively uniformly fractured shallow bedrock in the source area resulted in VOC migration deep into the bedrock system. Downgradient of the source area, groundwater flow direction is strongly influenced by a vertical fractured/weathered zone within the bedrock.

A fracture-trace analysis was used to identify potential fracture zones downgradient of the Site to determine potential migration pathways and assist in locating monitoring wells. An electrical resistivity survey was conducted to ground truth results of the fracture-trace analysis. Nested well clusters were then installed to evaluate horizontal and vertical flow patterns. Vertical profiles of hydraulic conductivity and VOC concentrations were developed using packer testing and groundwater sampling of discrete intervals within each borehole. Pumping tests were also conducted to evaluate interconnections within the bedrock and Site-wide hydraulic properties of the bedrock-fracture system.

Mass-flux analyses were conducted using the discrete hydraulic conductivity and VOC-concentration data to determine the vertical extent of VOC contributions from the relatively low permeability bedrock encountered with increasing depth at the Site. The mass-flux approach provided a practical and cost-effective alternative to installing and sampling additional deep bedrock wells in relatively low-permeability bedrock.

Results of the discrete VOC sampling and packer pressure testing provided hydraulic conductivity values and VOC concentrations of 10-foot test intervals within well boreholes. Mass flux was calculated using the hydraulic conductivity and VOC concentrations to quantify the relative contributions of VOCs from each test interval. Total mass flux for an entire well bore was calculated by adding the individual mass flux values for each interval. The ratio of the mass flux calculation of each test interval to the mass flux calculation of the entire well bore was used to quantify the relative percent of the total mass flux contributed by the corresponding bedrock test interval. Profiles of mass flux calculations for each well bore demonstrated a significant decrease in mass flux with depth. These data were used to limit the number and depth of additional deep bedrock well clusters installed during the investigation.

Background

The investigation was conducted at a 10-acre active trucking terminal located in Massachusetts. The facility includes a 35,000 square foot (feet²) terminal building and a 4,500-feet² maintenance garage (Figure 1). The Site is located within the Ipswich River Basin. The Site and surrounding properties are zoned for industrial use. The facility has been used as a trucking terminal since its construction in 1967. The Site was designated a Tier I Priority Site by the Massachusetts Department of Environmental Protection (MADEP) following the detection of volatile organic compounds (VOCs) in groundwater, that potentially contributes to two public-water supply wells located within one-half mile of the Site. The source of VOCs is attributed to historical releases by a former tenant of the maintenance garage between 1975 and 1988 into a catch basin located approximately 30 feet north of the maintenance garage (Figure 1). The primary VOC compounds detected at the Site include tetrachloroethylene, chlorobenzene, dichlorobenzene isomers, trichlorobenzene isomers, and trichloroethylene. By 1999, the vertical and horizontal extent of VOCs in bedrock was delineated at up to 1200 feet long, 350 feet wide, and 185 feet deep. Delineating a plume with these dimensions in fractured bedrock using conventional investigative techniques would typically be very costly and time consuming. Using the mass-flux approach combined with other assessment methods resulted in an accurate and comparatively low-cost investigation.

Hydrogeologic Setting

The Site is underlain by five to 40 feet of overburden deposits consisting of poorly sorted sand and gravel with cobbles. Bedrock at the Site consists of crystalline rock including granite, diorite, and gneiss. The upper bedrock surface is highly irregular and appears to be saprolitic and gradational for several feet from highly weathered to competent rock. There is a bedrock high to the north of the maintenance garage where the overburden is very thin and the depth to bedrock is only 4 to 7 feet below land surface (bls). The bedrock surface appears to slope downward to the southwest. A northwest-to-southeast trending fractured or weathered zone within the bedrock is located just southwest of the Site (Figure 1). Groundwater flow is to the south-southeast and strongly influenced by the characteristics of the upper bedrock.

Field Investigative Methods

Investigation of this Site involved many of the typical challenges faced when defining groundwater flow and contaminant transport within fractured bedrock. Experience gained during the process emphasized combining a variety of exploratory techniques to complete the investigation.

The investigation included installing, gauging, and/or sampling of 69 monitoring wells; performing slug tests; analyzing groundwater samples; conducting fracture-trace analysis; conducting a 72-hour pumping test; conducting a surface geophysical survey; borehole packer testing/vertical profiling; and calculating the mass flux of VOCs in the bedrock aquifer. Mass-flux analyses were useful in resolving the question of how deep to drill in bedrock.

Nested Well Clusters

Subsurface field investigations included installing 69 monitoring wells, installed as either single wells or in nested well clusters, at 27 locations. Wells were installed at various depths to evaluate the vertical distribution of VOCs and to evaluate vertical hydraulic gradients. Well clusters can include wells in the shallow (unconsolidated overburden) zone and five successively deeper bedrock zones identified as R1, R2, R3, R4, and R5. Monitoring well locations are shown on Figure 1. The systematic installation of multiple-well clusters was very significant in providing a three-dimensional monitoring-well network with which to analyze horizontal and vertical groundwater flow and VOC migration.

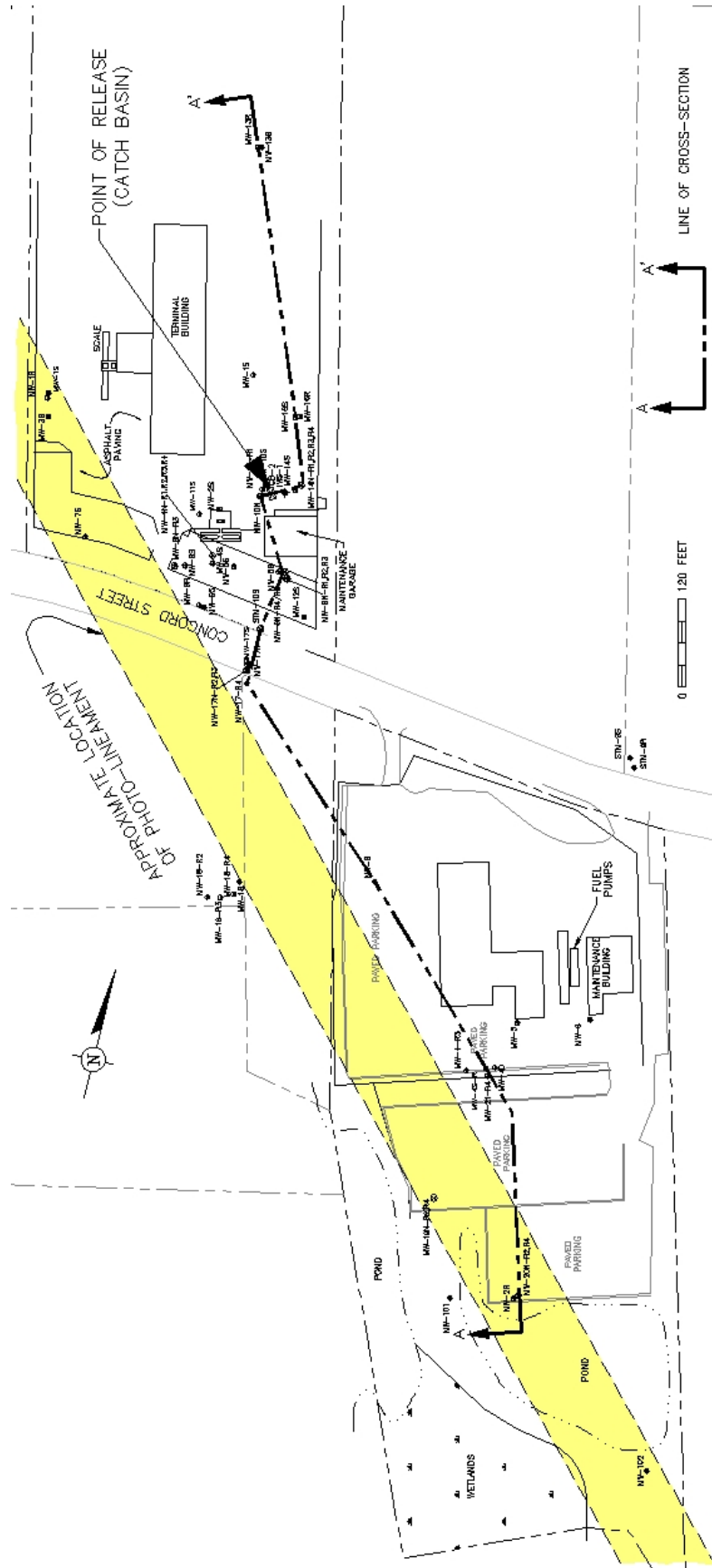


Figure 1. Site Plan

Initial bedrock investigations in the vicinity of the source area involved bedrock boring, packer testing and monitoring-well installation in the bedrock to a depth of 107 feet bls. Packer testing and sampling was then conducted to evaluate VOC concentrations at 9 intervals between 40 and 105 feet bls. The packer-testing results indicated increasing concentrations of VOCs with depth. Based on packer-testing results, two nested bedrock monitoring wells were installed. Information obtained through the installation of these monitoring wells made it apparent that high levels of VOCs were present in groundwater within the deep bedrock in the vicinity of the source area and potentially downgradient of the source area. Subsequent installations of additional well clusters including deeper wells in the R4 and R5 zones were used to complete the horizontal and vertical delineation. These wells were installed in an iterative phased manner, by evaluating existing groundwater flow and chemical data and results of fracture-trace analysis and geophysical surveys.

Fracture-Trace Analysis

A fracture-trace analysis was conducted to identify potential large-scale bedrock fractures or structural features that could possibly influence groundwater flow near the Site. Results of the fracture-trace analysis identified several photo-lineaments in the vicinity of the Site. The nearest and most significant of these was located on the west side of the site trending northwest-southeast (Figure 1). Based on the results of the fracture-trace analysis and groundwater monitoring data, six additional offsite monitoring wells were installed at three locations in the vicinity of the lineament identified through the fracture-trace analysis. Weathered/fractured bedrock and relatively high VOC concentrations were encountered at two of the locations (MW-4-R3 and MW-17-R4), located in the vicinity of the mapped lineament. Uniformly competent bedrock and relatively low VOCs were found in a 4-well cluster (MW-18), installed south of the lineament

Electrical Resistivity Survey

An electrical resistivity geophysical survey was conducted to determine whether there was a bedrock anomaly indicative of a fractured or weathered zone corresponding to the lineament southwest of the Site. The electrical resistivity (direct current) shows variations among different geological materials. Within crystalline rock, variations in resistivity are primarily due to water content within fractures and weathered zones. Therefore, a fractured or weathered zone in the bedrock was expected to show a zone of relatively low resistivity within a background of relatively high resistivity. Three resistivity profiles were completed relatively perpendicular to the lineament as much as feasible, considering constraints such as buildings and fences. Results of the geophysical survey and existing hydrogeological data, showed a broad northwest-to-southeast trending fractured/weathered zone in the bedrock located southwest of the Site. A low resistivity zone up to 100-feet wide and as deep as 120 feet bls was identified at this location. The low-resistivity zone is consistent with the general location and orientation of the lineament identified by the fracture-trace analysis. The presence of a weathered and fractured bedrock zone was confirmed during the drilling of Monitoring Wells MW-4-R3 and MW-17-R4.

Vertical Profiling and Mass-Flux Analysis

Groundwater Sampling

Vertical profiling was conducted during the drilling program to evaluate the vertical extent of VOCs in bedrock up to 270 feet bls. Packer testing was performed at 10-foot intervals in five boreholes to determine VOC concentrations and hydraulic conductivity of each interval. A dual air-rotary drill rig was used to advance an 8-inch diameter open borehole to a pre-determined depth. Following completion of the borehole to the required depth, a service rig was used for performing the packer testing. The packer assembly consisted of two packers positioned 10 feet apart. Between the two packers, a submersible pump was positioned in the open borehole and was used to purge the 10-foot test interval when the packers inflated. The two packers were inflated using nitrogen from a tank on the service rig. The packer-test assembly also included a pressure transducer installed below and above the packer assembly to ensure the packers were properly seated. A groundwater sample was

collected from each 10-foot test interval and analyzed for VOCs. Test results provided a vertical profile of the VOC distribution in bedrock. However, groundwater sampling alone could not be used to accurately define the vertical limits of VOCs.

Hydraulic Conductivity Packer-Pressure Testing

Packer pressure testing was also performed at 10-foot intervals in the boreholes to determine the hydraulic conductivity of each interval. The packer pressure testing equipment consisted of an injection pump (Moyno type), a source of potable water, high-pressure water feed hose/piping, an impeller-type calibrated flow meter (range 1 to 100 gallon per minute (gpm)), pressure gages (range 10 to 100 pounds per square inch (psig)), dual inflatable packers, 10-foot perforated piping section, and a water-level indicator. The test procedure was based on the protocol developed by the United States Department of the Interior Bureau of Reclamation (USBR)¹.

The pressure testing was initiated by pumping water at a rate that developed a suitable injection pressure. The suitable injection pressure is a function of the size of the injection piping, test interval depth, and groundwater elevation in the well bore. Upon reaching the desired injection pressure, pumping was continued until the flow rate became steady. This was determined by monitoring and recording flow rate at one-minute intervals for a three to five-minute period while maintaining a constant injection pressure. The diameter and length of the perforated piping, diameter of the high-pressure hose/piping and elevation of the pressure gage and groundwater were also recorded. After the three to five-minute injection at a steady flow rate was completed, the test was repeated within the same interval at a different injection pressure and flow rate, and the average hydraulic conductivity was calculated for each test interval. Upon completion of the tests in one test interval, the packers were deflated and the test set-up was moved to another pressure test interval and the test procedures were repeated.

Using the packer pressure testing data, the hydraulic conductivities for ten-foot test sections were calculated using the following formula:

$$k = \frac{q}{2\rho LH} \ln\left(\frac{L}{r}\right) \quad \text{when } L \geq 10r$$

Where:

- k = hydraulic conductivity, cm/sec
- q = constant rate of flow into test interval, cm³/sec
- L = length of test interval, cm
- H = differential head of water at test interval, cm
- r = radius of the well bore, cm
- ln = natural logarithm

The data were entered into a spreadsheet and hydraulic conductivity values were calculated for each test in a selected interval. Average hydraulic conductivity values were calculated for each test interval in the well bore and repeated for additional well bores. An example of the calculated values is presented in Table 1.

¹ United States Department of the Interior – Bureau of Reclamation, 1989. Procedure for Constant Head Hydraulic Conductivity Tests in Single Drill Holes, USBR 7310-89.

Depth Interval: MW-19R - 45 to 55 (feet bls)

Clock Time	Elapsed Time (minutes)	Gage (psi)	Duration (minutes)	Volume (gallons)	Flow Rate (gpm)	Hc (feet)	K (cm/s)	Avg K (cm/s)
1032	0							
1033	1	15						
1034	2	15						
1035	3	15						
1036	4	15						
1037	5	15						
1038	6	15	5	1.70	0.34	46.30	2.70E-05	
1039	7	34						
1040	8	34						
1041	9	34.5						
1042	10	34.5						
1043	11	34.5						
1044	12	34.5	5	2.40	0.48	91.35	1.93E-05	
1045	13	68						
1046	14	68						
1047	15	69.5						
1048	16	69.5						
1049	17	70	4	4.25	1.06	173.35	2.25E-05	2.29E-05

Table 1. Example of Hydraulic Conductivity Calculations for a Test Interval

Mass Flux Calculations

Based on the levels of VOCs detected in groundwater in each packer-test interval, the mass flux approach was used to determine the vertical extent of VOCs in bedrock. The mass-flux approach is well-suited to low yield formations because the approach considers the volume of water available and the VOC concentrations in each fracture-zone interval to assess the overall contributions of each interval to the entire groundwater-flow system. A practical advantage of the mass-flux approach to delineating the vertical extent of VOCs in bedrock derives from the difficulty in collecting representative groundwater samples from packer- test intervals with very low hydraulic conductivities because the yield is so low that the results are not representative of groundwater quality in the formation. This is typically the case in deep crystalline bedrock when trying to demonstrate the vertical extent of VOCs.

The mass flux in each test interval was calculated using the following equation:

$$m = \frac{k_{average} I}{\chi} [C]$$

Where:

- m = mass flux in each test interval, $\mu\text{g}/\text{cm}^2/\text{s}$
- $k_{average}$ = average hydraulic conductivity of each test interval, cm/s
- I = horizontal hydraulic gradient, cm/cm
- ξ = soil porosity, unitless
- C = concentration of VOC in groundwater in the test interval, $\mu\text{g}/\text{L}$

The mass flux was estimated for each test interval in the well bore and the total mass flux for the entire well bore was calculated by adding the individual mass fluxes for each 10-foot interval. For intervals where the hydraulic conductivity was not directly measured, the hydraulic conductivity of the next shallower interval was assumed. The ratio of the mass flux calculation of each test interval to the mass flux calculation of the entire well bore was used to quantify the relative percent of the total mass flux contributed by the corresponding bedrock test interval. Profiles of mass flux calculations for each well bore demonstrated a significant decrease in mass flux with depth as shown on Figure 2.

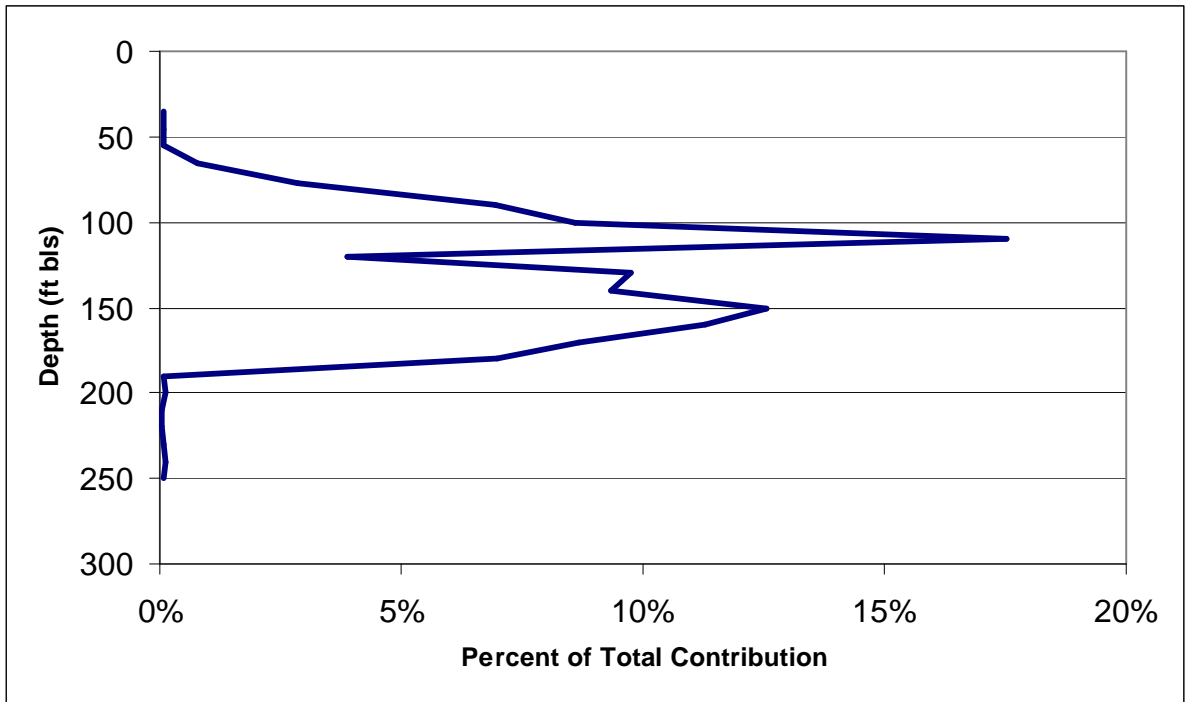


Figure 2. Vertical Profile of Mass-Flux Contributions in Borehole MW-6R

An example of the mass-flux calculations and results is presented in Table 2. Based on these calculations, 99% of the total mass flux occurs above 185 feet bls in the area of deepest groundwater flow and generally above 130-135 feet bls or less in other portions of the site. These data show that even if the VOC plume were to extend vertically to a depth of 500 feet or more, the mass flux for the bottom portion in each well bore would be insignificant relative to the mass flux of the relatively highly fractured zones in the upper bedrock zone.

Groundwater Velocity	0.08	(feet/day)							
Porosity	5.00%								
Groundwater gradient	0.0048								
Depth (feet bls)	Sampling Interval (feet)	Average K (1) (cm/s)	Total VOCs (µg/L)	Mass Flux (µg/cm ² /s)	Total Mass Flux per interval (µg/cm/s)	Percent Mass Flux per Interval (%)	Total Mass Flux in upper/lower aquifer (µg/cm/s)	Percent of total Mass Flux	Depth Interval (feet bls)
30 to 40	10	5.84E-04	15	8.41E-07	2.56E-04	0.1%			
40 to 50	10	5.84E-04	15	8.41E-07	2.56E-04	0.1%			
50 to 60	10	5.84E-04	15	8.41E-07	2.56E-04	0.1%			
60 to 70	10	4.18E-04	199	7.99E-06	2.43E-03	0.8%			
70 to 85	15	4.49E-04	452	1.95E-05	8.91E-03	2.8%			
85 to 95	10	4.49E-04	1653	7.13E-05	2.17E-02	6.9%			
95 to 105	10	4.49E-04	2049	8.83E-05	2.69E-02	8.6%			
105 to 115	10	1.65E-04	11382	1.80E-04	5.50E-02	17.5%	3.12E-01	99.4%	30 to 185
115 to 125	10	1.65E-04	2534	4.02E-05	1.22E-02	3.9%			
125 to 135	10	1.65E-04	6336	1.00E-04	3.06E-02	9.8%			
135 to 145	10	1.65E-04	6071	9.62E-05	2.93E-02	9.4%			
145 to 155	10	1.65E-04	8155	1.29E-04	3.94E-02	12.6%			
155 to 165	10	1.42E-04	8489	1.16E-04	3.54E-02	11.3%			
165 to 175	10	1.42E-04	6527	8.92E-05	2.72E-02	8.7%			
175 to 185	10	1.42E-04	5246	7.17E-05	2.19E-02	7.0%			
185 to 195	10	4.64E-06	1700	7.57E-07	2.31E-04	0.1%			
195 to 205	10	4.64E-06	3323	1.48E-06	4.51E-04	0.1%			
205 to 215	10	4.64E-06	1195	5.32E-07	1.62E-04	0.1%			
215 to 225	10	4.64E-06	1413	6.29E-07	1.92E-04	0.1%	1.89E-03	0.6%	185 to 255
225 to 235	10	5.36E-06	1759	9.05E-07	2.76E-04	0.1%			
235 to 245	10	5.36E-06	2245	1.15E-06	3.52E-04	0.1%			
245 to 255	10	5.36E-06	1417	7.29E-07	2.22E-04	0.1%			
				Total Mass flux for entire bore hole	3.14E-01		3.14E-01		

(1) - Where K value data were not collected, the value from the closest shallower known value is used.

Table 2. Summary of Mass Flux Calculations for Borehole MW-6R

Conceptual Site Model

Based on the Site history, hydrogeology, and distribution of VOCs determined from mass-flux analyses, a conceptual site model was developed. The source of VOCs in groundwater is attributed to releases between 1975 and 1988 by a former tenant into a catch basin located approximately 30 feet north of the maintenance garage. The VOCs released to the catch basin evidently leaked through and migrated outside of the catch basin structure. The bottom of the catch basin was constructed directly on bedrock and the bottom of the catch basin is at or below the average seasonal water table. Therefore, VOCs released through the catch basin moved directly into the groundwater within the surrounding fractured bedrock. Once in the groundwater system, VOCs moved in response to the hydraulic gradients. Based on aquifer and hydraulic conductivity testing, the bedrock in the vicinity of the source area exhibits moderate to low permeability, but appears to be fairly uniformly fractured and hydraulically interconnected. Consequently, the overall groundwater flow and constituent migration are similar to what would be expected in unconsolidated media. Due to the presence of a groundwater mound in the vicinity of the source area, constituents migrated horizontally to the south to southwest and also downward in the vicinity of the catch basin under the influence of a strong downward vertical hydraulic gradient. With increasing depth, groundwater flow is dominated by horizontal hydraulic gradients. Permeability and fracturing of the bedrock also dramatically decrease with increasing depth. To the south of Concord Street, groundwater flow from the Site intersects a northwest-southeast trending fractured/weathered zone. This zone acts as a preferred groundwater flow path and deflects groundwater flow to the southeast. Figure 3 is a contour map of total VOC concentrations in the groundwater depicting the extent of impacted groundwater associated with the Site and the overall groundwater flow pattern. At well cluster locations, the maximum total VOC concentration was used for contouring. The plume originates in the vicinity of the maintenance garage on the Site and extends across Concord Street. The shape of the groundwater plume traces the direction of groundwater flow as described above extending southwest from the source area and then south of Concord Street shifts to the southeast along the trend of the fractured /weathered bedrock zone.

Figure 4 shows Hydrogeologic Cross-Section A-A' with total VOC contours showing the area of impacted groundwater in section view. Based on these figures, the highest VOC concentrations are located directly beneath the source area and downgradient of the source area at depth where VOCs have migrated under the influence of a strong downward hydraulic gradient in the upper bedrock. This is also the portion of the Site where the deepest significant mass flux was measured (MW-6R). Further downgradient to the south, the contact between the fractured bedrock and dense bedrock rises and becomes quite shallow. There is also an upward hydraulic gradient that becomes more pronounced to the south, approaching the Ipswich River which appears to be the regional discharge point for the groundwater flow system.

Conclusions

Mass flux calculations were used to determine the vertical extent of VOC migration in wells with very low hydraulic conductivities at depth. The mass flux profiles demonstrate that there is a significant decrease in mass flux with depth, and that the dense bedrock that exists beneath the upper fractured bedrock delineates, in practical terms, the vertical extent of VOCs in groundwater. The mass flux approach, when used in conjunction with other assessment tools such as fracture-trace analysis and geophysical surveys, can result in a more efficient and targeted assessment program. Using a combination of these tools along with conventional assessment tools such as monitoring well installation and sampling can result in significant savings of time and money when assessing fractured bedrock.

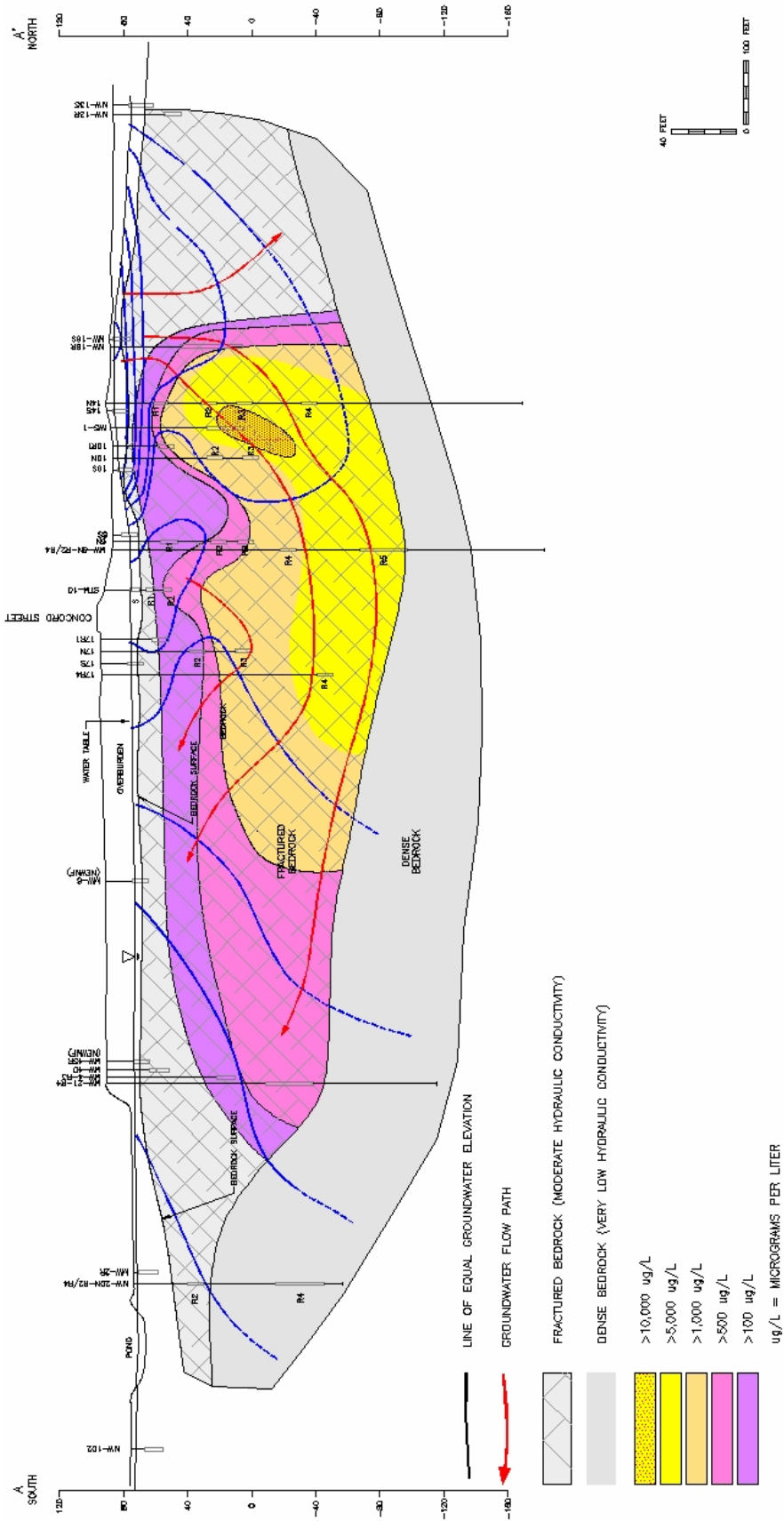


Figure 4. Hydrogeologic Cross-Section A-A Showing Distribution of Total VOCs