Camp Lejeune Pump-and-Treat Groundwater Decontamination Case Study Analysis

CIVE 686 – Term Project Report

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Abstract:

During the Second World War, in 1942, the military base named Camp Lejeune was built on the coast of North Carolina. It was used during that time as an amphibious training site. It is believed that between at least 1952 and 1987, the marines present at this camp were drinking water that was contaminated to a much greater extent than allowed by the regulatory norms (Bove, Ruckart, Maslia & Larson, 2014). The chemicals present were mainly trichloroethylene (TCE), perchloroethylene (PCE) and benzene. These volatile organic compounds (VOCs) can be responsible for birth defects and other illnesses (Sonnenfeld, 2001) and thus the supply pumps were shut in the mid 80s and unfortunately illegally reopened for a time after that. In 1996, remediation projects began using the pump-and-treat method. However, it is only in 1999 that the previous occupants of the camp were informed that they may have ingested the contaminated water.

We have decided to analyse the case and create our own pump-and-treat model to see how well we believe we could decontaminate the groundwater of VOCs at site 78 of Camp Lejeune using similar parameters as the case study. We approximate that the time that it would take for the groundwater in that region to have a VOC concentration of less than 10ug/L, assuming the water was saturated to begin with and neglecting desorption, would be 100 years with 2 side pumps extracting water at a rate of 2gpm, be 62 years with 2 center pumps extracting water at a rate of 2gpm. Center and side extraction well orientations using 20 extraction wells concluded in similar extraction times of approximately 2000 days.

We have also created possible theoretical situations that would alter the decontamination time. For one, we analysed what the effect of having a continuous source present, for example, a leaking gas tank, would cause to our overall decontamination time. When using our model with a tank of 0.016 L and with a 73% TCE and 27% benzene, it took … years for the entire groundwater to be decontaminated.

Literature Review:

Groundwater is an incredibly precious resource, it accounts for approximately 50% of all public water supply in the United States (McKinney & Lin, 1996). Unfortunately, this source of water can often be contaminated by leaking pipes, landfills, reservoirs and unplanned spills. Due to the importance of groundwater, these accidents need to be remediated. In 1989, more than 35% of remediation projects chose the pump-and-treat approach as their cleanup option (EPA, 1989) and the importance of this technology still carries on to this date.

The pump-and-treat method, described as the removal of contaminated groundwater by extraction wells and usually followed by its treatment prior to its disposal (Mackay & Cherry, 1989), is a very straight forward approach to groundwater remediation. It can be used for multiple purposes such as the containment of a contaminant source, the containment of a contaminant plume and for the reduction of the size of a contaminant plume. Being a mass transfer process, the contaminant mass removal rates can initially be high followed by a decline due to the increase in the influence of small-scale mass transfer limitations (Truex et al., 2017).

However, the kinetics of the contaminant are often much more complicated. For example, much of the contaminant may be sorbed to the particles present in the soil. Consequently, the soil itself acts as a source for the contaminant plume. Other variables, such as geological complexity, will have an effect on the movement of the plume within the soil as can be seen in the figure below:
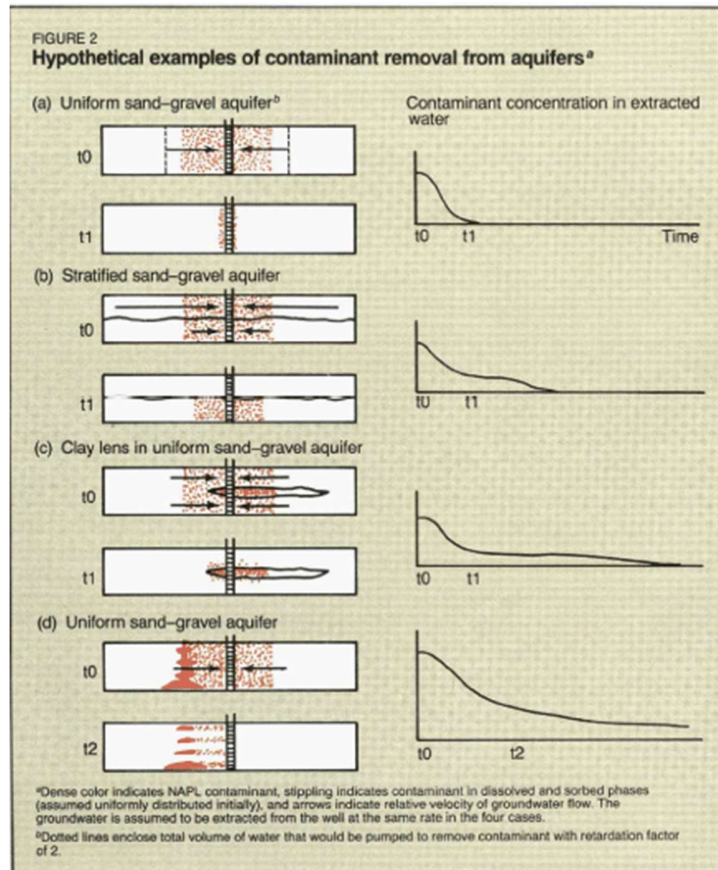
FIGURE 2
Hypothetical examples of contaminant removal from aquifers[a]

(a) Uniform sand–gravel aquifer[b]

Contaminant concentration in extracted water

(b) Stratified sand–gravel aquifer

(c) Clay lens in uniform sand–gravel aquifer

(d) Uniform sand–gravel aquifer

[a] Dense color indicates NAPL contaminant, stippling indicates contaminant in dissolved and sorbed phases (assumed uniformly distributed initially), and arrows indicate relative velocity of groundwater flow. The groundwater is assumed to be extracted from the well at the same rate in the four cases.
[b] Dotted lines enclose total volume of water that would be pumped to remove contaminant with retardation factor of 2.

Figure 1. Effects of geological complexities

These variations along with many others make it normally impossible to predict with accuracy the exact geometry and location of the plume, thus making it difficult to estimate the effectiveness and time required for a successful pump-and-treat remediation (Mackay & Cherry, 1989).

However, even with this uncertainty present, the locations of the extraction pumps can have a dramatic consequence to the effectiveness of the design. Ahlfeld and Sawyer (1990) presented an optimization model to design capture zones. This model was tested on several sets of wells and it was shown to be able to reduce the total pumping cost of a hypothetical plume by up to 37%. Additionally, it seems that the optimization of a system is more reliant on the location of the wells than their pumping rate (Huang & Mayer, 1997).

The optimal placement in a one-dimensional flow field with a symmetric plume along its flow direction is along the centerline of the plume (Huang & Mayer, 1997). Of course, this

is the case only when the permeability characteristics of a soil are homogenous. Unfortunately, real-life scenarios are much more complicated than this and require a case by case analysis for the optimal remediation strategy.

In real-life cases, the problem will be one consisting of three dimensions. To understand the potential distribution of a plume in such a scenario, it is important to analyse the transport mechanisms of the contaminant. These move by advection; being carried by the water in which they are dissolved or in colloidal particles to which they have been sorbed and by diffusion which dictates that the contaminant will move in the direction of the decreasing concentration gradient. In most pump-and-treat systems, extraction wells are placed downgradient of the plume, and the ensuing environing groundwater quality is monitored. This is a static approach, which may create stagnant regions within the aquifer, resulting in longer cleanup times. These can be minimized by utilizing a more dynamic approach through the continuous improvement of the understanding of the geologic, chemical and hydrologic environment in order to adapt the remediation process to its current needs (Hoffman, 1993).

In order to better understand the utility of the pump-and-treat system (PTS), it is important to compare it another commonly used remediation technique. One that has recently surfaced as a strong competitor is the use of a permeable reactive barrier (PRB). Due to its small energy and material requirements, it offers a potentially more economical solution. Despite this, it is important to compare these two technologies with the use of a life-cycle assessment in order to take all of their respective characteristics into consideration. This assessment was done with the use of a specific case study described by Higgins and Olson (2009) where the potential impacts of the model PRB originated from the presence of the ZVI reactive medium and the energy usage during construction while those from the PTS originated from the operational energy demand.

The reason why there is no operational energy demand taken into account for the PRB system is due to the passive nature of this technology. PRBs are installed strategically on

site to make groundwater pass through it. The reactive cells of the PRB then capture or degrade the contaminants with a reactive medium.

Additionally, before any comparison is made, it is necessary to understand that these technologies may not always be able to operate on every site. For example, PRBs are not the best suited for sites with deep and or wide plumes and sites that need very long-term remediation (Guo, Brusseau & Fogg, 2019).
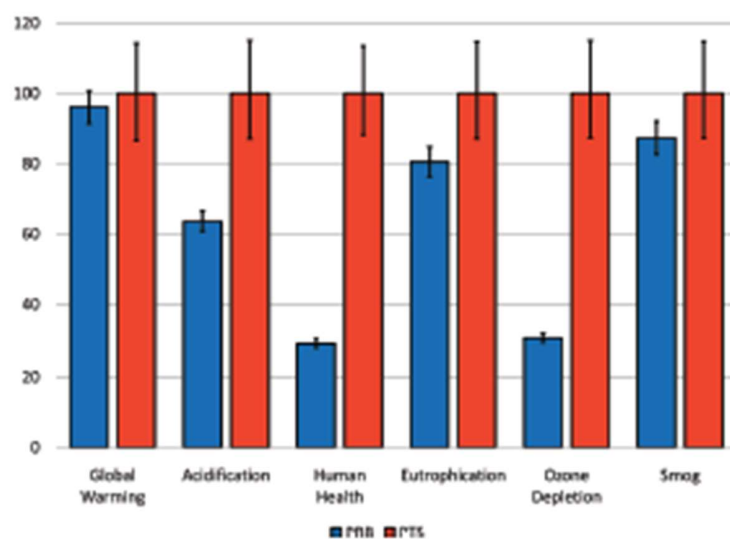

Figure 2. Environmental Impact Comparison (Higgins and Olson, 2009)

What is important to note from this chart is that although the PRB technique has a lesser impact in many fields, it is the case only if the barrier itself has a life-cycle of minimum 10 years, which is only assumed. Additionally, 95% of the environmental impacts illustrated in this graph for the PTS system originate from electricity requirement of the technology. Thus, the use of a renewable energy source would have an immense impact on the results.

As mentioned above, the importance of the duration of the life-cycle of the reactive material is extremely important to the relative impact of the technology.
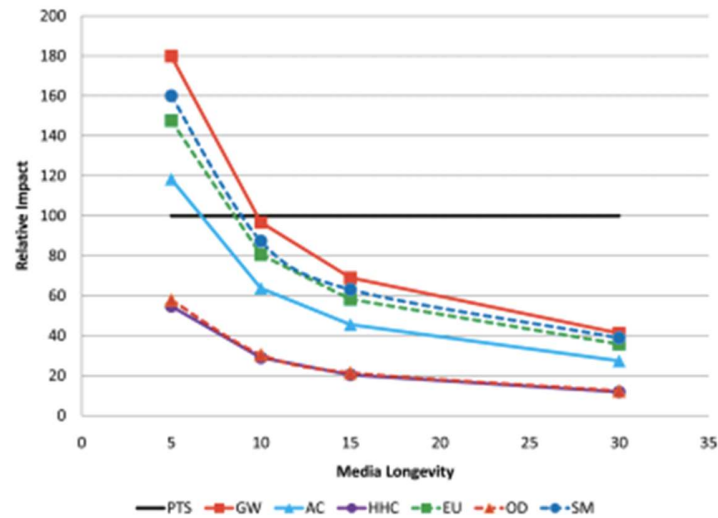
Figure 3. The Change in the Environmental Impact of PTS and PRB Over Time (Higgins and Olson, 2009). Abbreviations: GW, global warming; AC, acidification; HH, human health; EU, eutrophication; OD, ozone depletion; SM, smog formation.

Based on this comparison, the conclusion is that more research with varying factors (renewable energy, real PRB reactant life expectancy) needs to be done in order to truly compare both technologies properly. However, PTS in its traditional mode of operation, may not be the most environmentally conscience choice towards site remediation.

However, this method does present some technical advantages. It is not very intrusive approach and it has the ability to continuously update the groundwater data as it is extracted from the soil and can be used for soil vapour extraction (Brusseau, 2013). Additionally, the use of pulsed pumping may effect the efficiency of the PTS technology. However, whether its overall impact is positive or negative still remains questioned (Harvey, Haggerty & Gorelick, 1994). Another possibility is to inject water into the contaminated area to help "flush" the aquifer. This has been shown to be able to bring about operational benefits and if the water injected is the treated extracted water, could increase the sustainability of the pump-and-treat approach (Carver & Gertz, 2017).

The extraction of contaminant is usually slow in most environments. Consequently, it is therefore believed that the traditional pump-and-treat approach is usually more effective at

mitigating the propagation of a plume rather than its complete remediation (Mackay &
Cherry, 1989).

Case Study:

The case which will be analysed in this paper is the remediation of the groundwater project at Site 78 of the Camp LeJeune military base in Jacksonville, North Carolina. It is located within the Atlantic Coastal Plain geologic province which has a soil consisting of particles ranging from clay to gravel (NSERC, 2000). The camp is split by the New River in which most of the camp drains into.

The two most important aquifers related to the contamination of the groundwater at the site are the surficial aquifer, which is an unconfined aquifer and the Castle Hayne aquifer which is partially confined and the supply source of water for the camp and all of the 40 000 people present. For the majority of their area, these two aquifers are separated by an impermeable layer of approximately 9 feet deep. However, the locations where there is only a partial confinement leads to the communication between these two aquifers. This characteristic is most common in areas located near the New River and generates the possibility of vertical contaminant transport. However, for the case of our analysis, we will be solely focusing on the theoretical movement of the plume in the surficial aquifer.

The water table on location occurs 4 to 14 feet below ground-level and exhibits seasonal fluctuations. The surficial aquifer has a transmissivity of 75 square feet per day, resulting in a protentional production rate of approximately 2 gallons per minute. When comparing this to the Castle Hayne aquifer, it becomes clear why it is preferred for water extraction with a transmissivity ranging from 4300 to 7300 square feet per day resulting in a production ranging from 50 to 150 gallons per minute.

In terms of contamination, halogenated and non-halogenated volatile organic compounds (VOCs) have been shown to be present in both of these aquifers, it is believed that the latter originates from various petroleum products. Thankfully, the human health risk was determined to only be implicated with the groundwater and not the surrounding soil.

Initially, four wells were placed outside the perimeter of the plume in the direction of the groundwater flow (RW-1, RW-2, RW-3, RW-4) and planned to capture the plume once it migrated by dispersion. A pumping rate of approximately 1 gallon per minute generated a drawdown of about one foot in each well.

Further testing resulted in the understanding that the plume had stabilized and was not moving as initially predicted. As it was staying mostly stagnant, the 4 initial extraction pumps were eventually deactivated and two new ones (RW-10, RW-11) were put directly within the plume. This resulted in a decrease of the plume size as can be seen in the following images.
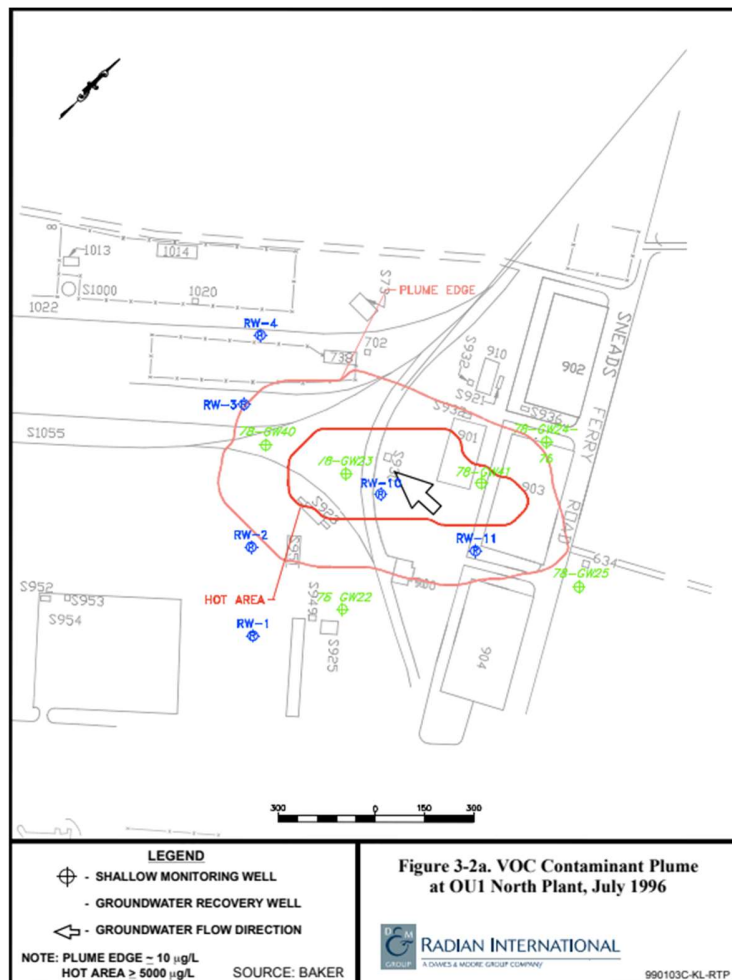
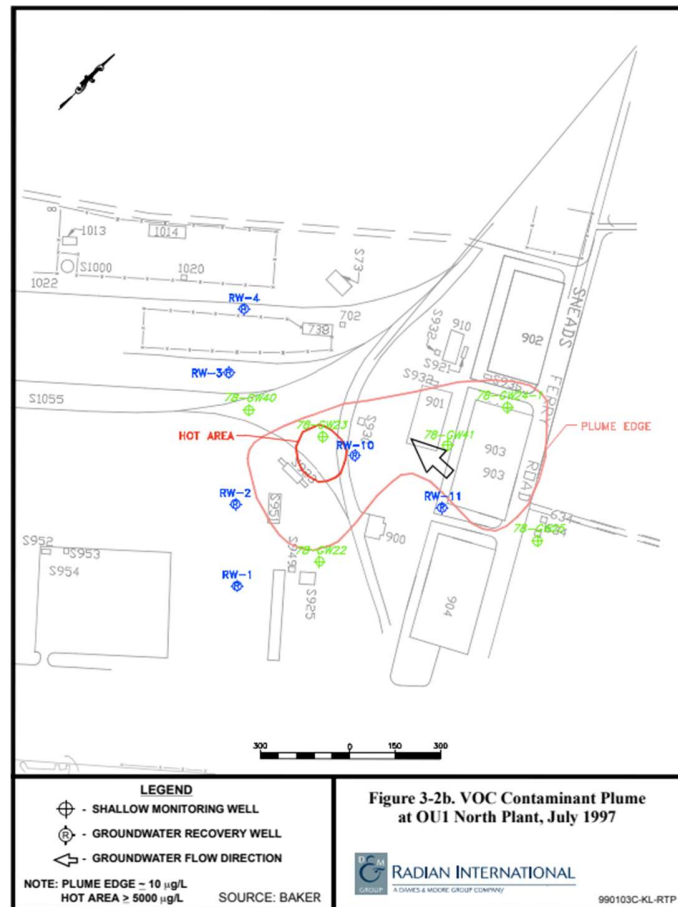Figure 4. Contaminant Plume Outline, July 1996 (NSERC, 2000)

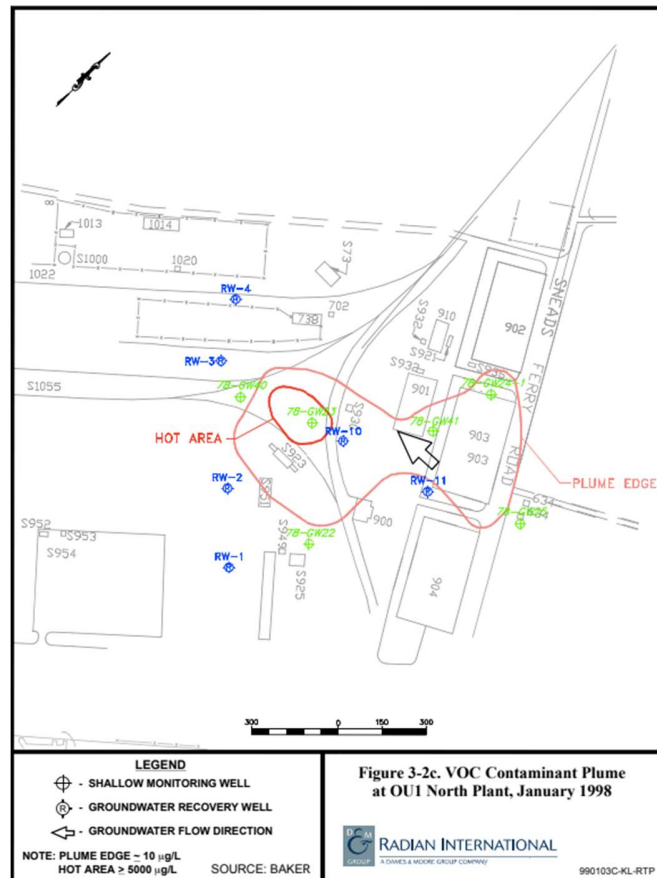Figure 5. Contaminant Plume Outline, July 1997 (NSERC, 2000)

Figure 5. Contaminant Plume Outline, January 1998 (NSERC, 2000)

Unfortunately, the plume of the "Hot Area" seems to have no noticeable decrease in size from July 1997 to January 1998. On the contrary, it seems to have extended slightly in the direction of the groundwater movement. It can thus be assumed that a more optimal extraction well placement exists. This location may be towards the North-West edge of the hot area plume as this would extract some of the "Hot Area" contaminated water as well as possible future propagation of this plume.

There were numerous discrepancies between the system design and the performance data. This is partially responsible for the high extraction cost. The cumulative mass removed over 2.5 years was 12 pounds making it an average cost of 27 000$ per extracted pound (excluding capital costs). What is interesting to note is that the first 6 pounds were removed during the first three months of operation, the remaining 6 pounds took 27 months to be

extracted. This leaves to believe that a pulsed pumping approach could significantly increase the efficiency of the remediation.

The volume extracted by the pumps was 10% that of the design and thus, over the last six months of the operation in 1998, 0.03 pore volumes of groundwater was removed. This is extremely slim compared to the typical range of 0.3 to 2 pore volumes (Cohen et. al., 1994). Consequently, additional pumps are necessary if the static pump-and-treat approach is to be effective.

Capture Zone Calculation

Following contamination plume identification via sampling of monitoring wells, the next step is to determine the least costly method of capturing the plume and separating it from the rest of the aquifer. Major design elements include: the number of pumping wells required, the positioning of the wells to ensure no contaminants slip between if multiple wells are used, and optimum well pumping rates.

Information required to calculate the proper well placements and the number of wells required for aquifer cleanup include:

- Depth and confinement of aquifer
- Regional hydraulic gradient
- Aquifer hydraulic conductivity or transmissivity and storativity
- Effective porosity of aquifer
- Permissible drawdown of water table
- Allowable contaminant levels
- Diameter of wells

Depth of surficial aquifer ranges from 4 to 14 bls (below land surface) to between 50 and 100 ft bls. An average thickness of the aquifer will be assumed to be 66ft. the drawdown of the water table due to 1 gpm pumping rate in the two active wells separated by a distance of 341 ft after approximately 0.5 years was measured to be 1ft. Though the surficial aquifer is unconfined, it is noted that since the drawdown of the water table in the shallow aquifer is small compared with the thickness of the aquifer the error associated with using confined aquifer solutions for capture zone calculation can be neglected (Javandel & Tsang, 1986).

Figure 4 shows the VOC contaminant plume of interest surrounding building 901 where the plume edge line signifies a concentration of 10 μg/L which is the limit of VOC concentrations above which need to be remediated. Surficial aquifer hydraulic gradients determined via potentiometric surface mapping was found to be approximately 0.003 ft/ft (RI, 92). Hydraulic transmissivity is given as 75ft^2/day. Average hydraulic conductivity

of the shallow aquifer is reported in (U.S. Department of the Navy, 1991) as $3.35\ ft/day$. Using Equation 1, Porosity of surficial aquifer is obtained by site investigations of local geography. As the site below the HPIA is composed of mainly silty sand (HPIAFS, 91), thus void ratio is estimated to be 0.25 to 0.49.

Equation 1. $$K = T/B$$

Where K is hydraulic conductivity, T is hydraulic transmissivity and B is the thickness of the aquifer.

Largest width of the plume perpendicular to the direction of groundwater flow must be contained within the capture zone. The dimensions of the plume zone ([VOC] > 10gμ/L) parallel and perpendicular to the direction of groundwater flow are approximately 1105 ft and 709 ft respectively (obtained from Figure 4.). Hot zone ([VOC] > 5000μg/L) has dimensions of 682 ft and 477 ft parallel and perpendicular to groundwater flow respectively.

Though it is unlikely that drawdown around extraction wells will be an environmental concern, two extraction wells will be used in further calculations in accordance with the actual remediation setup.

Storage coefficient of the surficial aquifer required for calculation of the drawdown caused by pumping is calculated from actual drawdown observations for 1 gpm of well pump rate over half a year. Using a well radius of $r = 0.25$ ft Equation 2. gives a storage coefficient of $S = 31.1$.

Equation 2. $$\Delta h = \frac{2.3Q}{4\pi KB}\{\log\frac{2.25KBt}{r^2S} + \log\frac{2.25KBt}{(2d)^2S}\}$$

Where t is time in days, Q is flow rate of wells and d is distance between two wells (341 ft).

Distance between streamlines far upstream from the wells for and optimal placement of two wells under a uniform groundwater flow is given by Equation 3. Substituting the maximum width of plume perpendicular to groundwater flow as y_{max}, maximum required flow Q is calculated to be 79.7 ft^3/day, or 0.414 gpm. This is the minimum extraction pump rate required for the containment of the plume, however, for the remainder of the study a rate of 2gpm per well will be used instead due to

Equation 3.
$$y_{max} = \frac{2Q}{Bv}$$

Where v is the Darcy flow rate through the aquifer

Equation 4.
$$v = Ki$$

Where K is hydraulic conductivity and i is the local hydraulic gradient.

Using this result the optimal spacing between the two pumps calculated using Equation 5. is 113 ft.

Equation 5.
$$y_{between\ wells} = \frac{Q}{\pi Bv}$$

The capture zone shape can be finalized using equations and which are the distance from line of wells to stagnation point and distance between streamlines at line of wells respectively. Final dimensions of capture zone is given in Figure 6.

Equation 6.
$$x_{stag} = \frac{Q}{2\pi Bv}$$

Equation 7.
$$y_{well\ line} = \frac{Q}{Bv}$$

Drawdown of the pumping wells was re-calculated using theses values and remained approximately 1ft in each well.
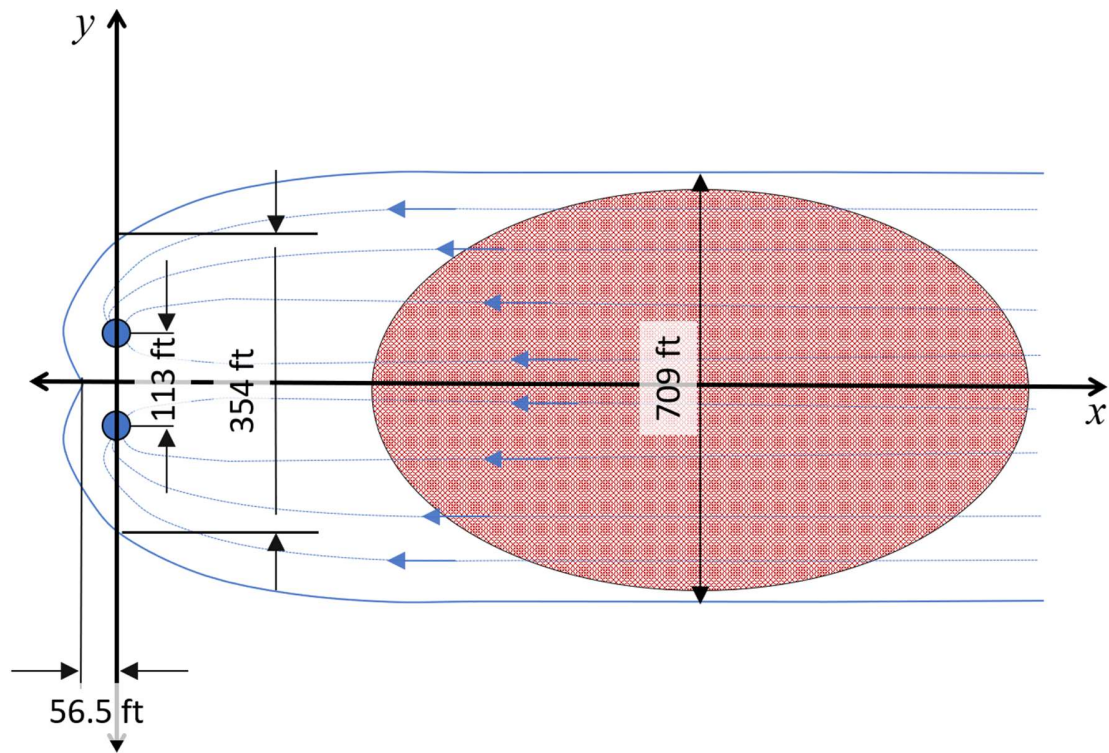
Figure 6. Capture Zone Model

2D Contaminant transport

Three scenarios of contaminant transport into the wells will be analysed. Actual remediation at Hadnont Point industrial area involved the removal of all VOC sources prior to isolation and pump and treat of the VOC plume. A simplified version of this will be analysed in the first scenario with the plume initialized as a mass transport of an instantaneous source, 1D advection, 2D Dispersion contaminant with 2 extraction wells. The second scenario will look at the time requirement for cleanup with 20 wells. The third and fourth scenario will be moving the 2/20 extraction wells to the center of the plume instead. The fifth Scenario will involve the pump and treat cleanup of a plume with a hypothetical continuous source of TCE and benzene.

No source Scenario

Dispersion is an aquifer field specific parameter dependent on fluid turbulence, fluid shearing in interconnected porosities, and porosity level. It is thus difficult to estimate accurately without direct large-scale field testing. For this current analysis the ratio of dispersion coefficients is obtained from plume shape using equation for the 1D advection and 2D dispersion scenario. This coincides with out assumption that the plume is oriented with its x-axis parallel to the direction of groundwater flow and dispersion is vertically homogenized (same through the thickness of the aquifer). Absolute values of the dispersion

Equation 8.

$$D_x = \frac{\sigma_x^2}{\sigma_y^2} D_y$$

Where D_x, D_y are coefficients of dispersion in the x and y directions respectively and σ_x, σ_y are plume shape parameters described in Figure 8.
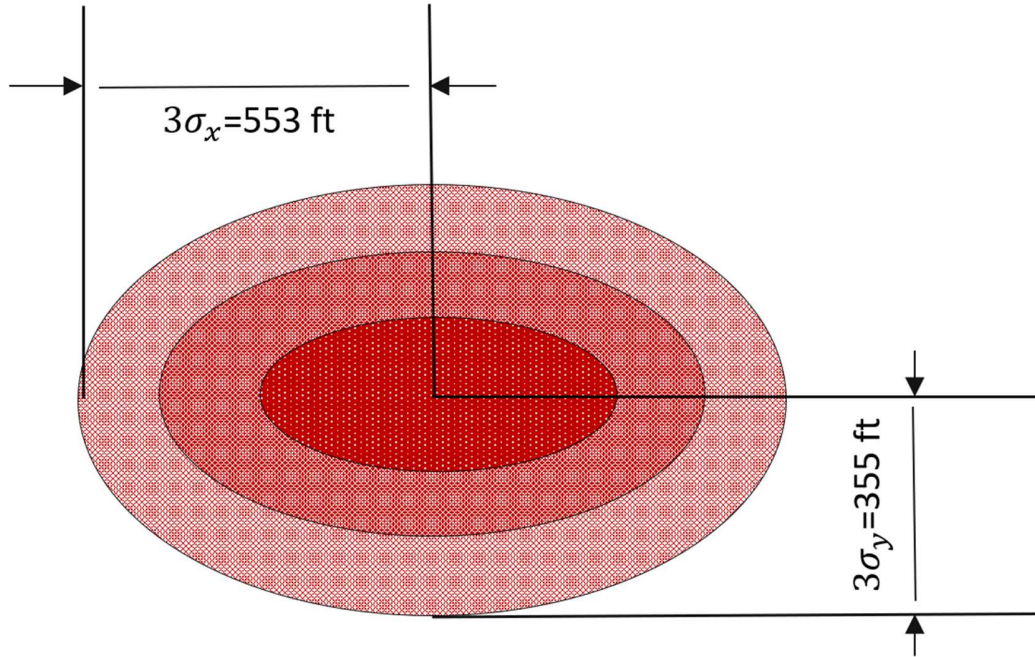
Figure 8. Plume Shape Parameters

coefficients are more difficult to obtain, and so effort was made to perform literature review to make use of values from a similar aquifer. The chosen aquifer (Hoehn and Santschi 1987) was one from the lower Glatt Valley of Switzerland. Similar hydraulic conductivity and silty sand content was observed in this aquifer and the resulting reliability of dispersity value was judged by (Gelhar 1992) to be acceptable. Furthermore, the instantaneous source assumption allows for simple analysis of an isolated, source-less contaminant plume.

Finally, initial plume VOC concentration data was extrapolated using Equation 9. and actual plume concentrations at two locations (edge of plume and hot area). The resulting initial plume contour is shown in Figure 7.

Equation 9.
$$C(x, y, t) = \frac{C_0 A}{4\pi t \sqrt{D_x D_y}} e^{-\frac{(X-vt)^2}{4D_x t} - \frac{Y^2}{4D_y t}}$$

Where C_0 is the instantaneously injected tracer concentration over an area of A. t is time since injection of tracer and X, Y are distances in the x and y directions respectively from the center of gravity of the plume.

Figure 7. Initial Plume Contour
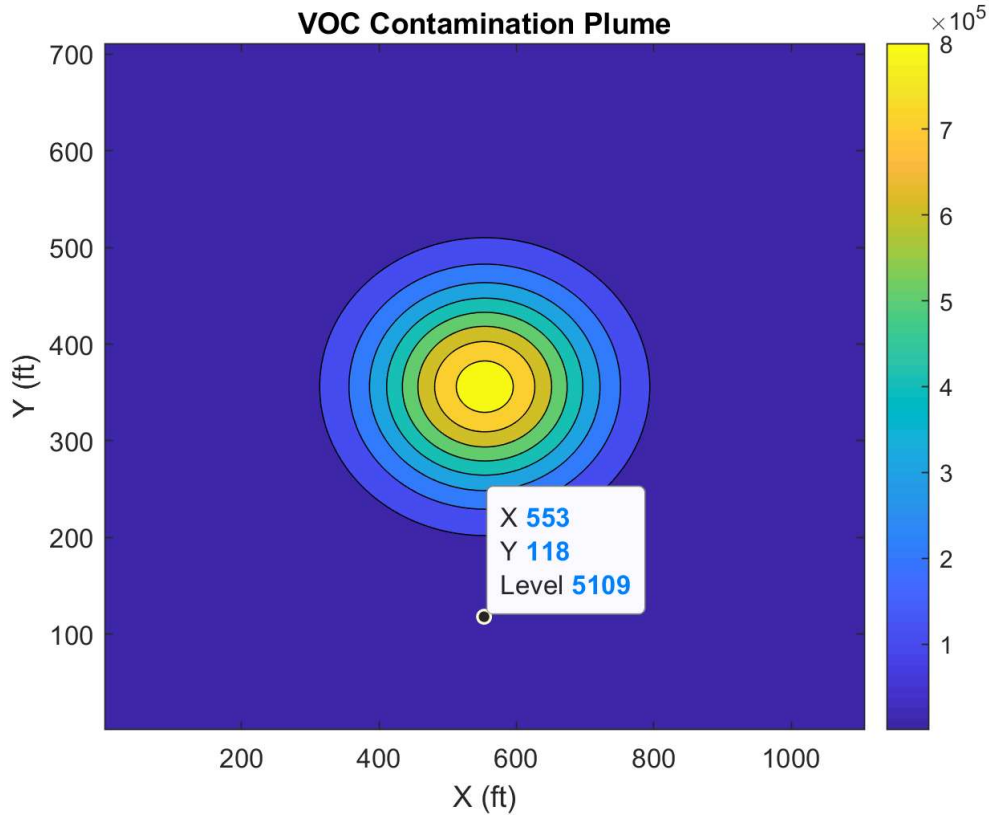
The equations for 1D advection and 2D dispersion of a non sorbing contaminant plume are shown as Equation 11. and 12. Advection of the plume in the direction of groundwater flow (x direction) is dependent on v is the linear seepage velocity of the water through the aquifer pores. Aquifer velocity is assumed to be unchanged by the presence of pumping wells as drawdown around the wells is insignificant.

Equation 11.

$$\left(\frac{\partial C}{\partial t}\right)_{advection} = -v\frac{\partial C}{\partial x}$$

Equation 12.

$$\left(\frac{\partial C}{\partial t}\right)_{dispersion} = D_x\frac{\partial^2 C}{\partial x^2} + D_y\frac{\partial^2 C}{\partial y^2}$$

Results for numerical solution were compared with analytical solution for robustness and thus creating a framework for alternative boundary condition inputs. Numerical approximations used are listed in Equation 13., 14., and 15.

Equation 13.
$$\frac{\partial C}{\partial x} = \frac{C(i, j + 1, t) - C(i, j - 1, t)}{2\Delta x}$$

Equation 14.
$$\frac{\partial^2 C}{\partial x^2} = \frac{C(i, j + 1, t) - 2C(i, j, t) + C(i, j - 1, t)}{\Delta x^2}$$

Equation 15.
$$\frac{\partial^2 C}{\partial x^2} = \frac{C(i + 1, j, t) - 2C(i, j, t) + C(i - 1, j, t)}{\Delta x^2}$$

Mass Transfer from Continuous NAPL Source

Though in actuality, fuel and solvent contaminant sources were removed prior to pump and treat initiation, continuous source scenarios are of interest in evaluating the cost efficiency of various degrees of source removal. As there is scarce information on the leakage rate and total volume of leakage/spill sites, an idealised continuous source will presumed to be in contact with the hot zone of the plume. Furthermore, it will be assumed leakage rates are much higher than dissolution rates into the water and so the actual leakage rate will be neglected through out our calculations. Instead, the source will be a hypothetical NAPL form with contact area of 4 ft by 4 ft. Finally, the only other information required will be the mass transfer parameters of the contaminants themselves and the total size of the contaminant source. A standard fuel storage tank of 160 L volume will be the hypothetical source of contaminant for this calculation. 10% of contamination in the tank will be assumed to remain and gradual release according to dispersion kinetics will ensue.

Contents of the tank derives from highest concentration species from include:

- 72% by mass of TCE
- 28% by mass of Benzene

Mass transport parameters of these compounds are listed in Table 1.

Table 1. Mass Transport Parameters of TCE and Benzene

	TCE	Benzene
Molecular mass (g/mol)	131.4	78.11
Diffusion coefficient (cm2/hr)	0.0303	0.0666
Saturation concentration in water (mg/L)	1100	1780
Longitudinal aquifer dispersivity (ft)	74.33	74.33
Transverse aquifer dispersivity (ft)	22.3	22.3
Density (kg/L)	1.61	0.876
Mass transfer coefficient (cm/hr)	0.0259	0.013

TCE values obtained from (Chrysikopoulos, Hsuan & Fyrillas, 2002)

Equation 16. mass transfer of benzene and TCE into the existing plume.

Equation 16.
$$\frac{dC}{dt} = k_t^i \frac{A}{V} (C_{eq}^i - C^i)$$

Where C_{eq}^i is the equilibrium concentration of contaminant i in water, C^i is the current concentration of the contaminant in water k_t^i is the mass transfer coefficient, A is the area of contact and V is the volume represented by that area in our 2D homogenization. C_{eq}^i is given by the molar fraction of contaminant i multiplied by the saturation concentration of contaminant i in water. This molar fraction is updated according to mass of TCE and benzene concentrations remaining in the NAPL source at every time step.

In the current scenario the area of contact per volume of the mixing area is the depth of the aquifer^-1. Cleanup for this scenario is achieved when the TCE reaches cleanup standards as TCE makes up the bulk of the contaminant source and has a lower cleanup standard than benzene. Dispersion for this scenario is calculated using an aquifer scaling approximation from Neumann, 1990.

Equation 17. $\qquad\qquad\qquad\qquad \alpha_x = 0.32 x^{0.83}$
Equation 18. $\qquad\qquad\qquad\qquad \alpha_y = 0.3 \alpha_x$

Where α_x and α_y are mechanical dispersion coefficients in the x and y direction respectively and x represents the total length that will be traveled in the direction of groundwater flow. Diffusion contribution to hydrodynamic dispersion is negligible compared with mechanical dispersion and so the overall hydrodynamic dispersion coefficients is taken as equivalent to mechanical dispersion coefficients multiplied by aquifer velocity.

The following scenarios were considered for pump and treat cleanup of the Camp Lejeune

- Scenario #1: No source pump and treat scenario with two wells at the side of the plume
- Scenario #2: No source pump and treat scenario with two wells at the center of the plume
- Scenario #3: No source pump and treat scenario with twenty wells at the side of the plume
- Scenario #4: No source pump and treat scenario with twenty wells at the center of the plume
- Scenario #5: Continuous benzene and TCE leaking fuel tank source with two wells at edge of plume.

Resulting times to cleanup for the scenarios are as follows in table 2

Table 2. Cleanup Times

	Numerical Times to cleanup of 10 ug/L (days)	
Number of wells	2	20
Wells to side	36616	2020
Wells in center	22810	2410

An overall trend of lesser time was observed for well placement inside plume, however this orientation also shifts the position of the capture zone as well and further calculation would been to be done to observe what rate the wells need to pump at in order to retain the plume n the capture zone. For the 2 well scenario it is likely that it would take 100 years for the side well orientation which coincides with the case study as they observed little plume movement with only 2 extraction wells placed.

Placing 20 wells as suggested by the case study reduced time to complete cleanup greatly to around 5 years. This value is unrealistic however as placing more well does not necessarily guarantee the extraction rate will be multiplied as we have assumed. Drawdown of the surficial aquifer would need to be considered and a limit for extraction rate established. Placing 20 wells at the center of the plume comparatively took almost the same amount of time to cleanup due to the main contribution being the imposed capture zone flow rate and the fact that the plume was further away from extraction wells when wells were to the side made little difference.

Figures 9., 10., 11. and 12. show the average concentrations at the wells for each of the first 4 scenarios. Differences can be seen distinctively for when the maximum concentrations were being extracted by the wells.
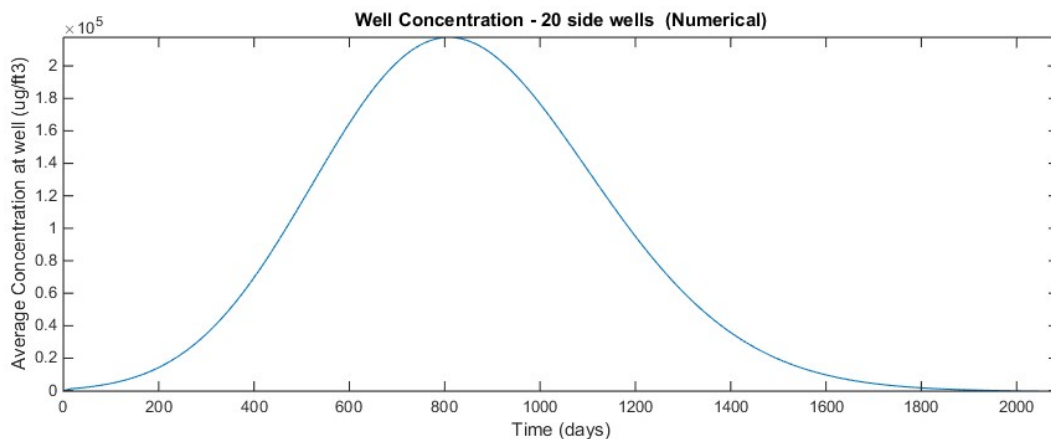

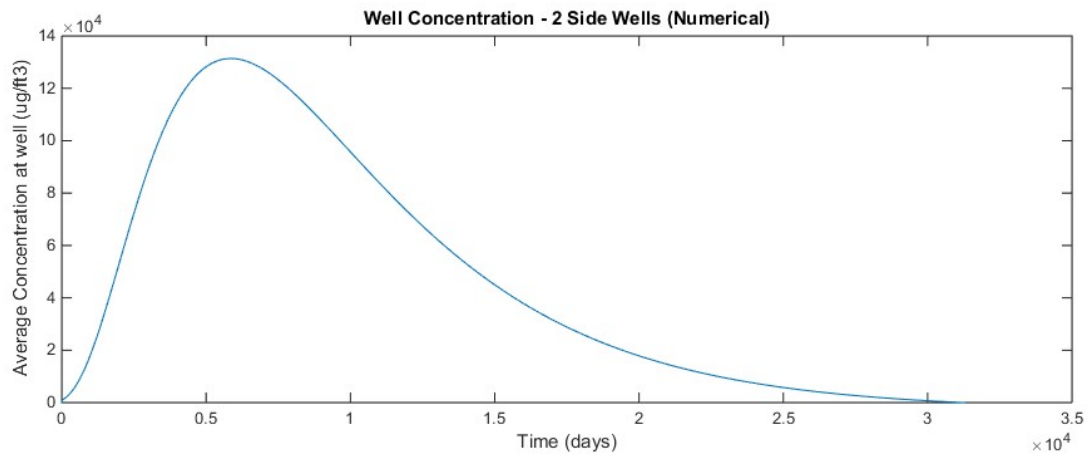Figure 9. Well Concentration – 20 side wells (Numerical)

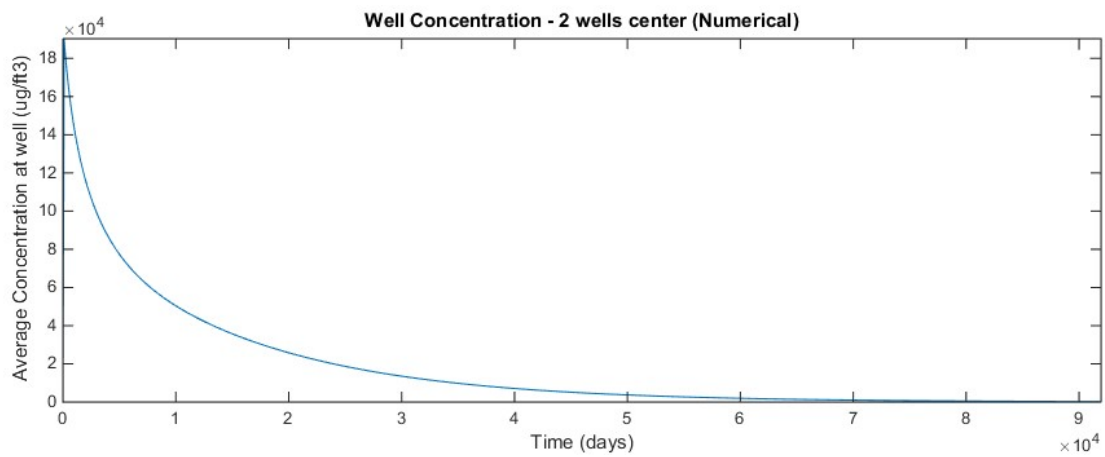Figure 10. Well Concentration – 2 Side Wells (Numerical)

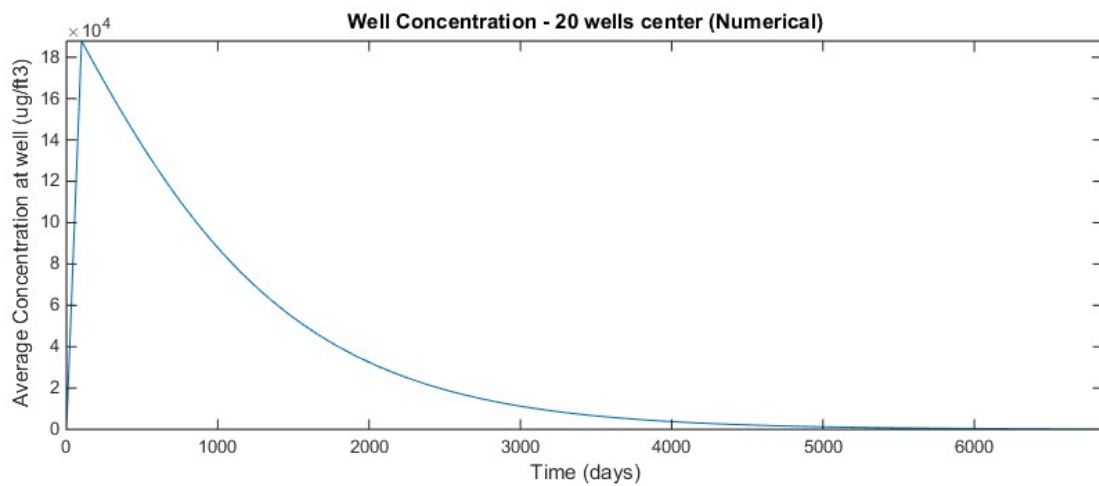Figure 11. Well Concentration – 2 Wells Center (Numerical)

Figure 12. Well Concentration – 20 Wells Center (Numerical)

The next scenario shows a continuous dissolution of TCE and benzene from a hypothetical storage tank NAPL source of 16 L. From intermediate snapshot of plume (Figure 13), a distortion of plume shape can be observed due to continuous source input. During the life cycle of cleanup, all remaining contaminant is dissolved into the aquifer, thus cleanup time is not too far from cleanup time with no continuous source. The difference can be made up from the slightly different dispersity coefficients taken. If a greater source was used with dissolution time approaching the the original no source cleanup time, a pulsed pumping scheme of contamination extraction may be implemented. Figures 14 and 15 show the average concentration of TCE and benzene in the capture zone respectively.
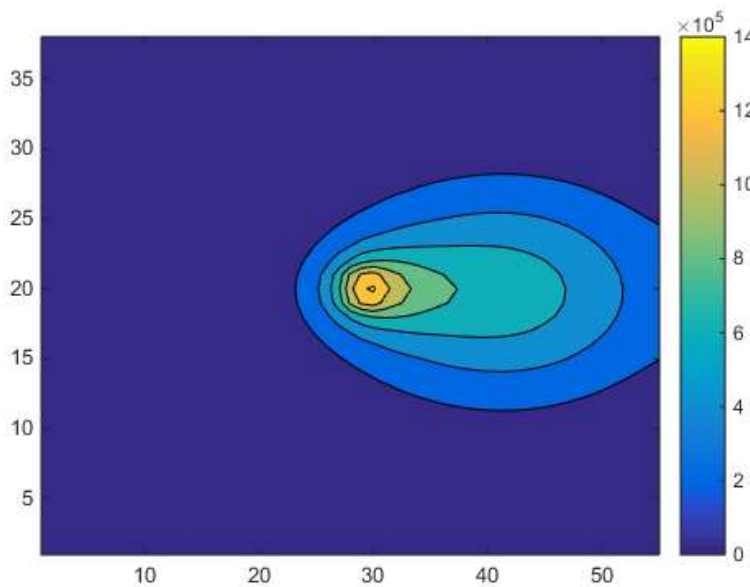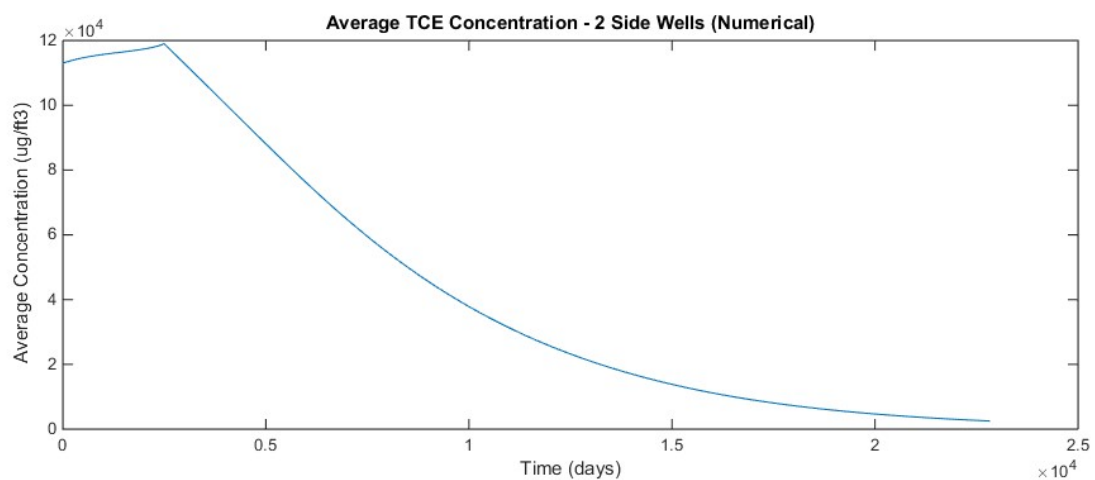

Figure 13. Continuous source TCE plume shape

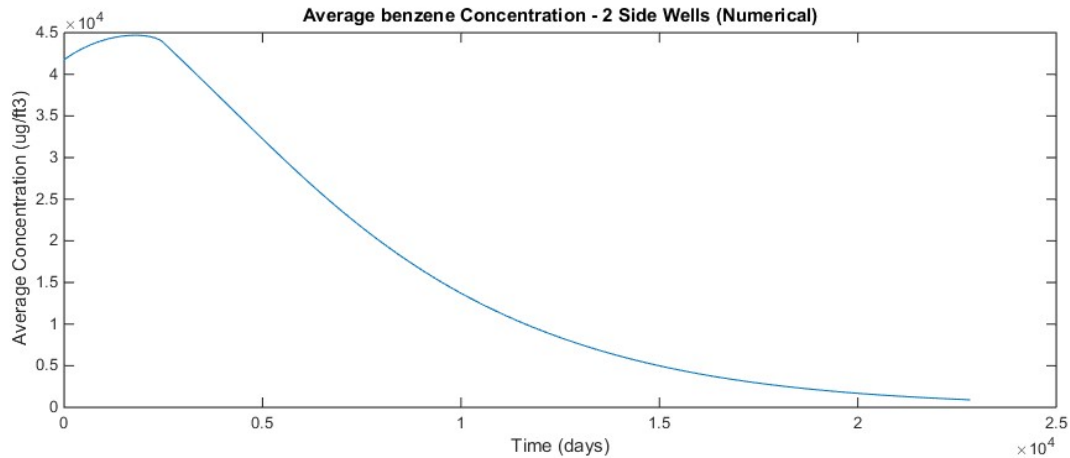Figure 14. Average TCE concentrations in capture zone.

Figure 15. Average benzene concentrations in capture zone.

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