**EPA**

United States
Environmental Protection
Agency
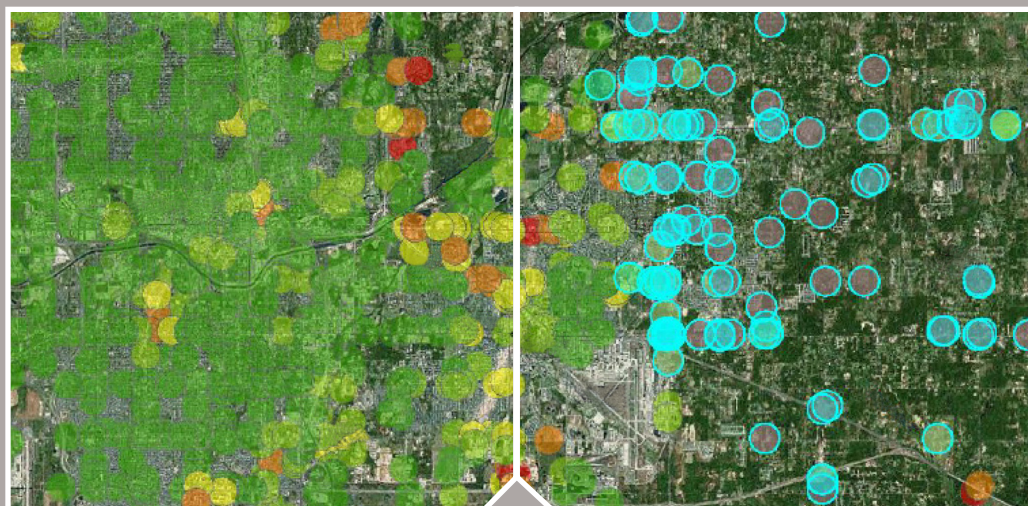
# Relationships between Private Domestic Wells and Underground Storage Tanks: Evaluation of Mapping and Plume Transport Tool Implementations



Office of Research and Development
National Risk Management Research Laboratory | Groundwater, Watershed, and Ecosystem Restoration Division

# Relationships between Private Domestic Wells and Underground Storage Tanks: Evaluation of Mapping and Plume Transport Tool Implementations

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# Abstract

Well water from private domestic wells (hereafter private wells) is often not tested as private owners are exempt from sampling requirements of the Safe Drinking Water Act.  Numerous incidents of contamination of water in private wells have been reported, however.  Potential contaminant sources, like underground storage tanks, are widespread across the United States.  This report describes a pilot project using a geographic information systems (GIS) application that was developed to display locations of underground storage tanks and indicate the likelihood that there are private wells within several selected distances.  A few locations can be selected by the application user or, when data from an entire state or region are available, a large area can be viewed at a glance.   The pilot project was developed for Oklahoma, because of the large amount of freely available data, but could be extended to other locations where data are available.

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## Quality Assurance

This project was conducted under an approved U.S. EPA quality assurance project plan (ORD Project QA ID #G-GWERD-0019367).   Evaluation of the data and estimates methods used for the software tool described herein are presented in the EPA report EPA 600/R-17/175,  titled "Proximity of Private Domestic Wells to Underground Storage Tanks: Oklahoma Pilot Study".

# Introduction

Ground water contamination carries the risk of impacting private domestic wells (hereafter simply "private wells"). Because these wells are not covered by the Safe Drinking Water Act, testing of the water supply is at the discretion of the owner (U.S. EPA 2004). In many cases well owners are unaware that water should be tested, what parameters should be tested, or how to go about testing (see Ridpath et al., 2016). As a consequence, private well water often goes without testing, and numerous incidents where people have been exposed to contaminated water have been documented (e.g., Ander et al. 2016, DeSimone et al., 2009, Schaider et al. 2016, U.S. EPA 2002).

In the U.S., a common ground water contaminant source that potentially threatens well users is underground storage tanks (USTs). Petroleum product releases have been reported from over 530,000 underground storage tanks, with almost 71,000 cleanups remaining to be completed (US EPA 2016). One of the main potential pathways for exposure to petroleum hydrocarbons originating from leaking underground storage tanks is the consumption of water from private domestic wells.

The purpose of this Geographic Information Systems (GIS) Application (APP) is to demonstrate a method to show the relationship between point sources of subsurface contaminants and private wells. Because of the large number of reported releases, underground storage tanks are taken as the potential source of leaks for this work.

# Private Well Locations

Knowledge of private well locations varies by state. Most of the data, however, are limited by undercounting (record keeping may have only started recently, or all required records are not reported), lack of easy access to data (e.g., data held as paper or PDF copies, cost to requester for release of data), or legal restrictions (Weaver et al., 2017). Because of these limitations we adopt the estimation methods developed by Weaver et al. (2017) and Murray et al., (2017) which use the 1990 census as a baseline, and projects forward in time using census and/or state agency private well records. Originally the work focused on a pilot study in Oklahoma (Weaver et al., 2017), but was extended by Murray et al. (2017) to the entire U.S. Additionally, Murray increased the resolution by reducing the spatial data unit from the census block group (average area of 42.12 $km^2$) to the census block (average area of 0.826 $km^2$).

## Underground Storage Tank Locations

Upon its creation by the Superfund Amendments and Reauthorization Act, the federal underground storage tank program was delegated to the states. Each state manages their program according to state priorities and the federal government collects only selected data on each program. The locations of regulated or leaking tanks are held by the states. With data from an entire state, obviously, the locations of tanks with the most potential for impacting private wells can be seen at a glance. Where this information is not available, locations can be selected and the number of potentially-impacted wells be determined.

## Locations of Potential Impacts

In the following example regulated tanks are shown as circles of a specified radius. In this case 1500 ft was chosen, although 1000 ft is also available, and for single tanks any distance can be chosen. This distance corresponds to a maximum reasonable benzene, toluene, ethylbenzene and xylene (BTEX) plume extent based on empirical data analysis and plume modeling (see Appendix A: Assessment of Plume Extents). The distance roughly follows from plume studies and modeling (see Appendix) which show an upper bound of BTEX plume length on this order of magnitude. Site-specific investigation, however, is the only way to determine the actual direction and extent of contaminant plumes. The information presented in this APP is intended as a screening approach for planning:

- If a tank (or planned tank location) is nearby, are there private wells within a specified potential impact zone?
- Should cleanups or inspections be prioritized in areas with a high density of private well use?

In areas where datasets giving the locations of all underground storage tanks are available, a location can be selected on the map and estimates of the number of private wells, housing units and population can be generated for user-input potential impact zone areas (Figure **1**). This usage of the tool addresses the first question above. Details on the procedure for using these features are found in the section "Single-Tank Analysis".

Areas of co-location of underground storage tanks and high reliance on private wells can thus be seen at a glance (Figure **2**). Details on the procedure for using these features are found in the section "Opening Screen".

The approach of using a potential impact zone follows from fixed-radius methods of wellhead protection (U.S. EPA, 1994). Absent a site-specific investigation, the direction of ground water flow is not known. Because of preferred directions of ground water flow (in response to pressure gradients), however, it is unlikely that the entire area of each potential impact zone would be impacted.
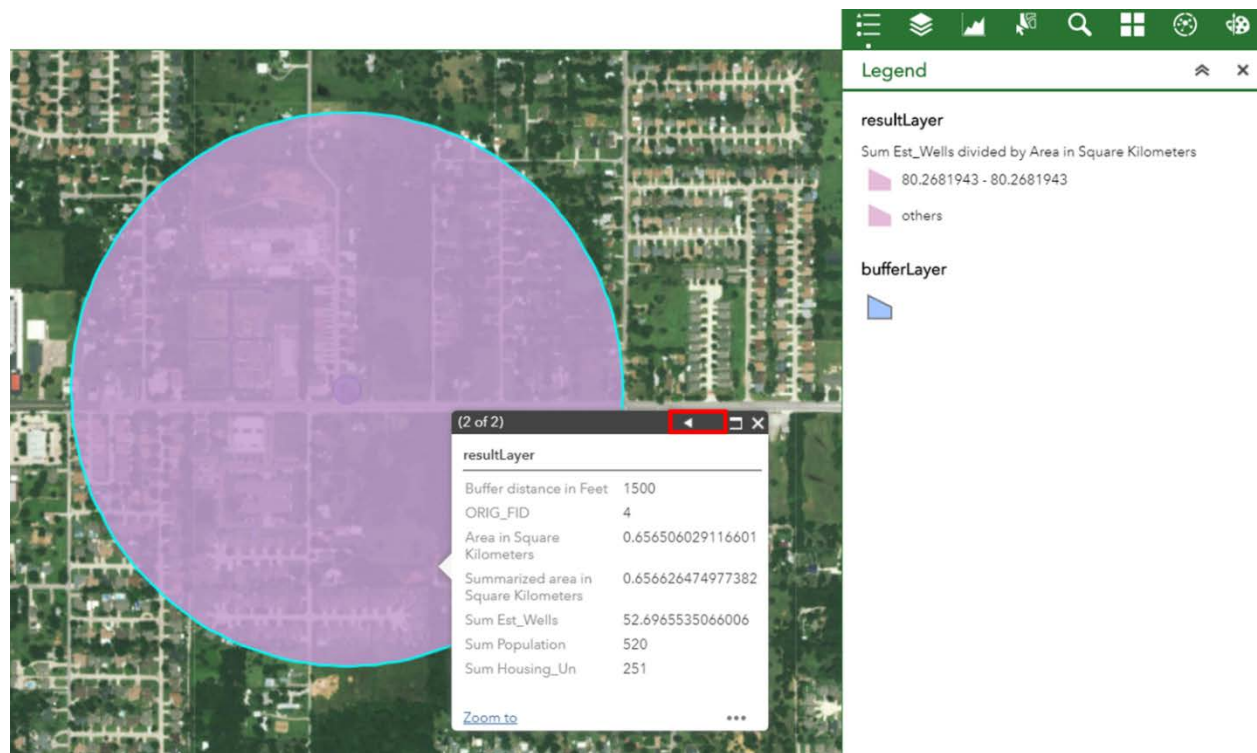
Figure 1.  Example of selected tank site showing 1500 ft radius buffer distance, estimated number of private wells (53), housing units (251) and population (520).
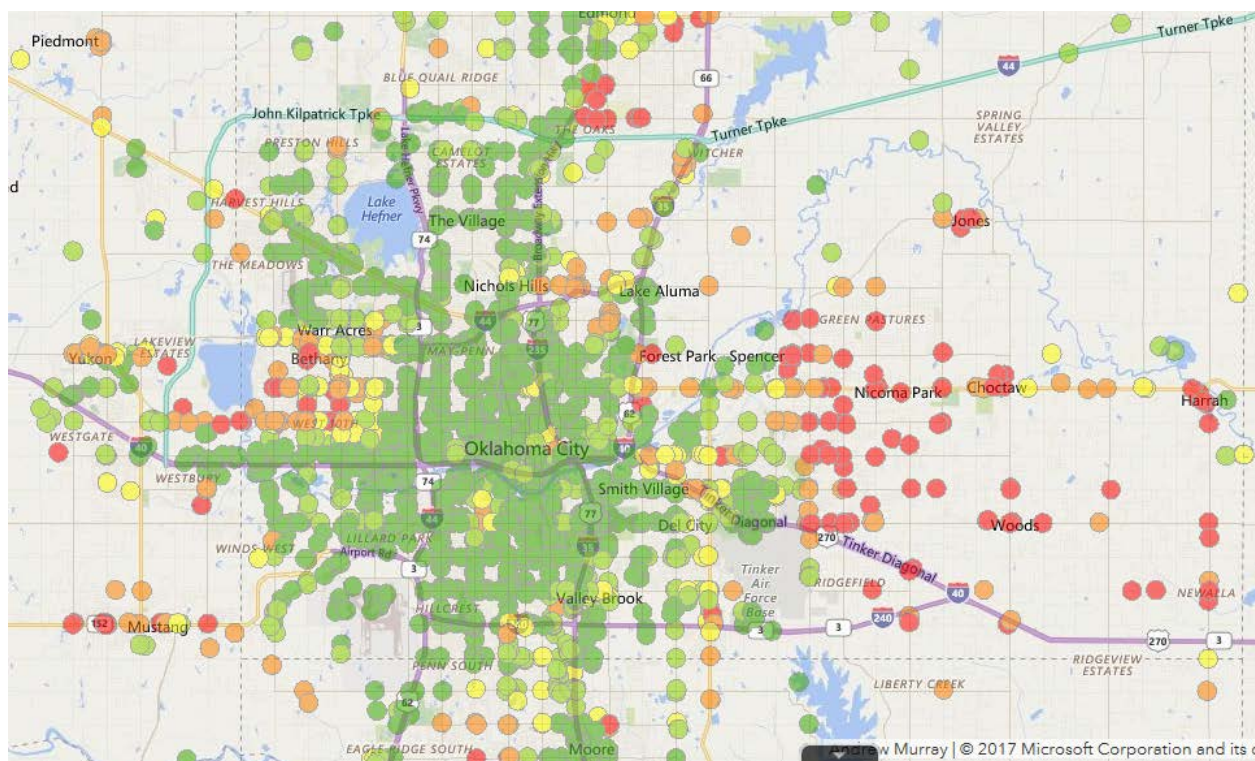
Figure 2. Locations of regulated tanks in the Oklahoma City area. Circles represent 1500 ft radius zone around tanks which are colored by the estimated numbers of private wells within the zone. Red is the highest density of wells in the 1500 ft radius and green the lowest. Areas with most red-colored circles generally lack public water or are in areas of legacy historical private well use.

# Evaluation

Assessment of the spatial relationship between underground storage tank sites and private wells requires certain assumptions. These are necessary for two reasons. The first is because of data limitations the locations of all private wells are not known. Further, locations of known private wells in the U.S. are not compiled at the national level. Existing state records are generally limited, because in most states, reporting requirements have been imposed only recently. Thus in this work, private well locations are estimated by the methods developed by Weaver et al. (2017).

The second reason is that the potential for contaminant impact on a well depends on factors influencing movement and degradation from the source of contaminants to the well. The question is "does the contaminant reach the well at a high enough concentration to create a health risk?" Answering this question from mapping application is limited because contaminant transport depends on factors that are not mapped in detail on a national basis. These factors include hydraulic conductivity, sorption and heterogeneity of aquifer materials; the amounts of available electron acceptors to drive biodegradation;

and the local gradient of the water table. The later can be estimated in a gross fashion from surface topography, but is limited by heterogeneity, well pumping rates, and impervious surface cover.

As noted in Appendix A: Assessment of Plume Extents, empirical data and modeling independently provide estimates of the plume extent. Empirical data are limited by the number of sites examined and the quality of site data; modeling is limited by assumptions built into the models, data limitations, and, in this case, the lack of calibration to field conditions. Plume extents thus calculated from these sources can best be viewed as a guide for site-specific investigation, as it is site-specific investigation, monitoring, and sampling that establishes actual plume extents.

Thus the results provided in this report are best viewed as guides to program planning and additional investigation as map-derived data are limited and assumptions are used for determining both private well locations and the extent of contamination from a presumed source.

# Application Documentation

## Introduction

By combining publicly available data on Oklahoma's regulated underground storage tanks and estimates of domestic groundwater well use at the Census Block level, the end user is able to use this application to explore the varying potential vulnerability of contamination statewide for Oklahoma. Application was made to Oklahoma for demonstration purposes. For use in other states, tank location data could be added to the EPA-derived estimates of private well usage. The following describes the capabilities of the application and is a general guide on how to use those capabilities.

## Opening Screen

The application opens up to a map viewer with three basic components. The first, and most basic, are the navigation controls in the top left of the window which allow you to zoom in and out, navigate to the initial map extent (home button) or navigate to your location (currently limited to Oklahoma). The second set of components are the application tools on the right-hand side. Here you will find tools which will allow you to manipulate the map display, as well as to facilitate some simple statistical analyses. The third component is the attribute table which will allow you to view specific information relating to facilities with USTs as well as information on specific tanks. Each of these will be discussed in detail below.

## Application Tools



 The application toolbar contains eight distinct tools; the legend, operation layers, charts, select, search, basemap selection, analysis, and draw.

## Legend



Clicking on the legend reveals the symbology of all the currently selected operation layers. When the application is first opened, the default operational layer named "Wells Within 1500 ft" will appear in the map viewer and the legend will appear as is shown in the figure to the right. This layer portrays a 1500 ft potential impact around each facility with an underground storage tank and is color coded based on the estimated number of domestic wells that it contains.
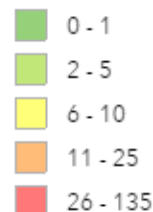


## Operational Layer List

The layer list displays all of the available layers that can be added to the map. It will initially look like this figure to the right, but clicking on the left-hand arrows will expand the categories and reveal individual layers. The available layers are the initial 1500 ft potential impact zone layer, an alternative 1000 ft potential impact zone, and a layer showing estimated domestic wells at the Census block level.



To account for preferred plume transport directions, sectors are drawn within the circles to indicate the preferred direction based on the surface topography and an assumed 60% variation in the gradient direction (Haitjema and Mitchell-Burker, 2005 ). This approach is based on the premise that ground water flows in directions that mimic the surface topography. Because of a number of factors, the actual ground water flow direction may differ from that predicted from surface topography. Key factors, especially changing infiltration, pumping from wells which can be highly variable, and subsurface heterogeneity, require site-specific analysis and investigation. Thus the results from the transport tool are presented as a first approximation which requires further site-specific data collection, which is likely to require field sampling. Again, site-specific investigation is the only way to determine the actual direction of contaminant transport, but there may be some information gained in estimating the major directions of
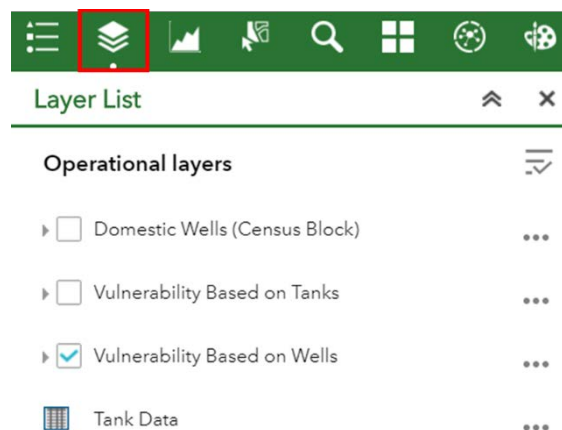
transport.  Impacts should not be ruled out because of the locations of the sectors.   Sectors for the 1000 ft and 1500  potential impact zones are available.

Lastly, in the "Vulnerability Based on Tanks" category, there is a layer that shows the number of physical tanks within a distance of 1500 ft from any point in the state.  When using the Vulnerability Based on Tanks category, turn off the "Well's within 1500 ft" layer, to ensure only one layer is made visible at a time to reduce the chance of confusing one or more layers with similar color schemes.
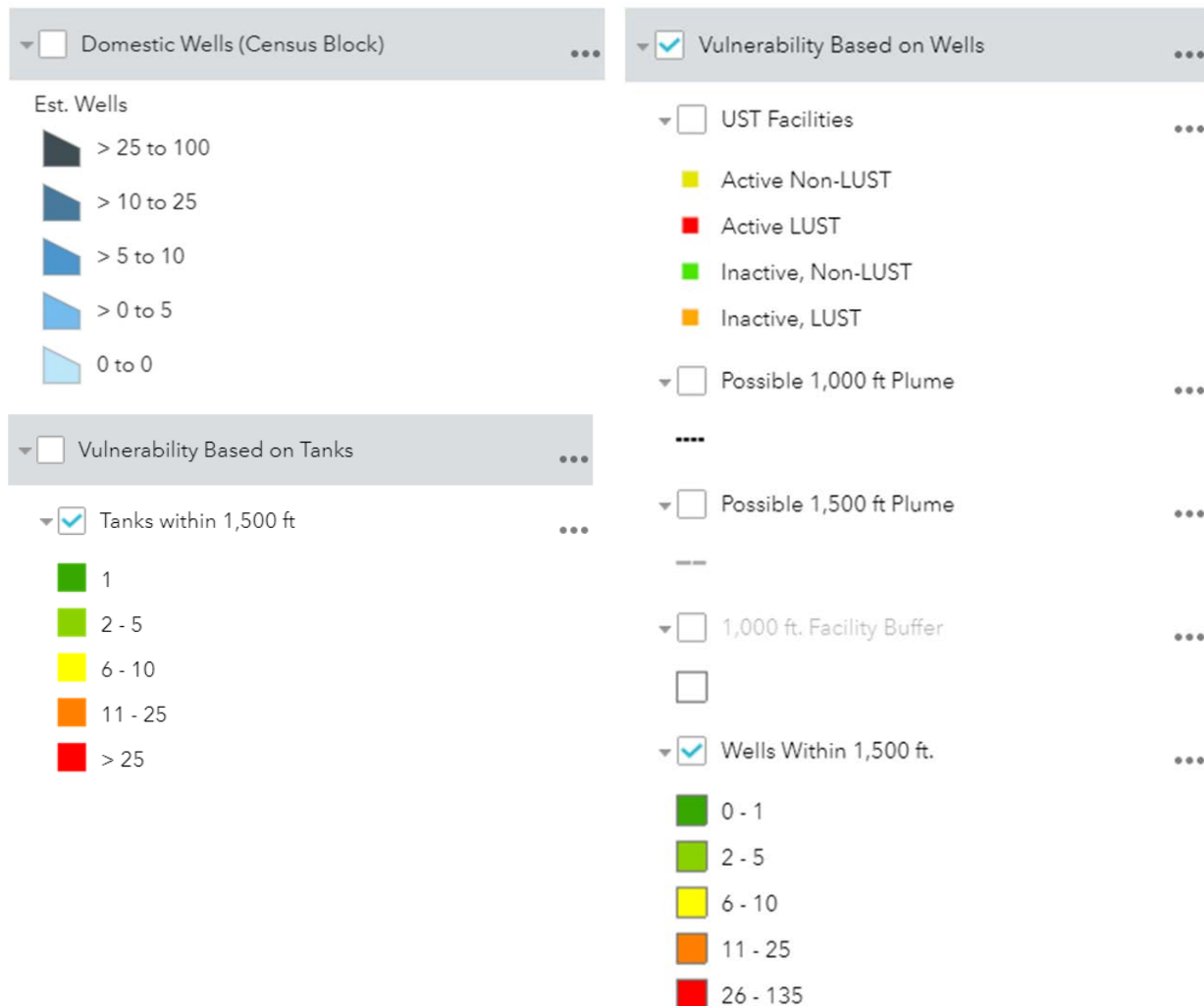


**Charts**

The one available chart is titled "Estimated Number of Wells within Varying Distances", this chart allows the end user to define a geographic area and then to visualize the estimated wells potentially vulnerable to LUST contamination through a bar graph that will display estimated number of wells for the estimated 1000 and
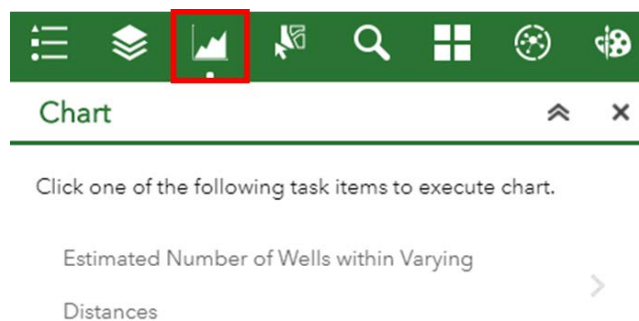
1500 ft sector areas, and the 1000 and 1500 ft potential impact zones.

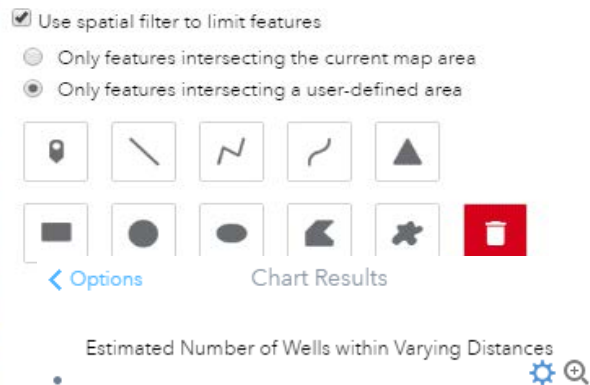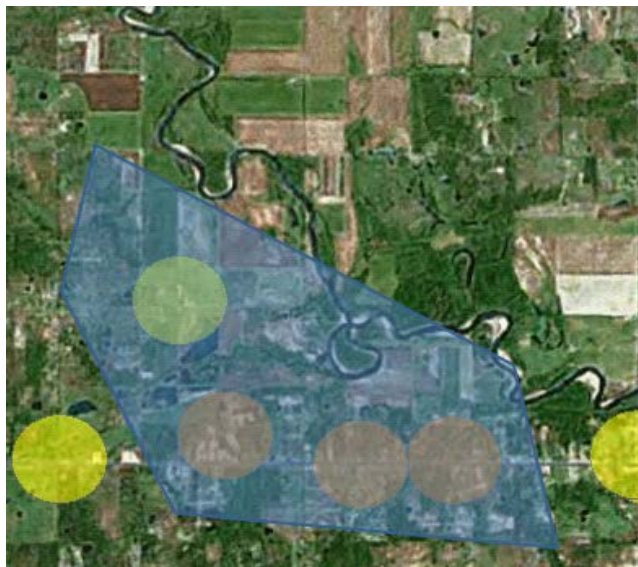To create a chart, select "Estimated Number of Wells Within Varying Distances", then click "Use spatial filter to limit features". Then you can either use the current map extent, or predefine an area which will let you draw a specific area of interest, then click apply.



☑ Use spatial filter to limit features

○ Only features intersecting the current map area

◉ Only features intersecting a user-defined area

‹ Options          Chart Results

Estimated Number of Wells within Varying Distances



The resulting chart pops up in the window. A magnifying glass is visible in the top right corner of the results which will pop out the graph to make it more readable. Red flags appear in the map viewer which denote the facilities that were included in the graph. The x-axis represents estimated number of wells that are vulnerable. Blue denotes the 1000 ft sector, orange denotes the 1500 ft sector, grey represents the 1000 ft potential impact zone, and yellow represents the 1500 ft potential impact zone.
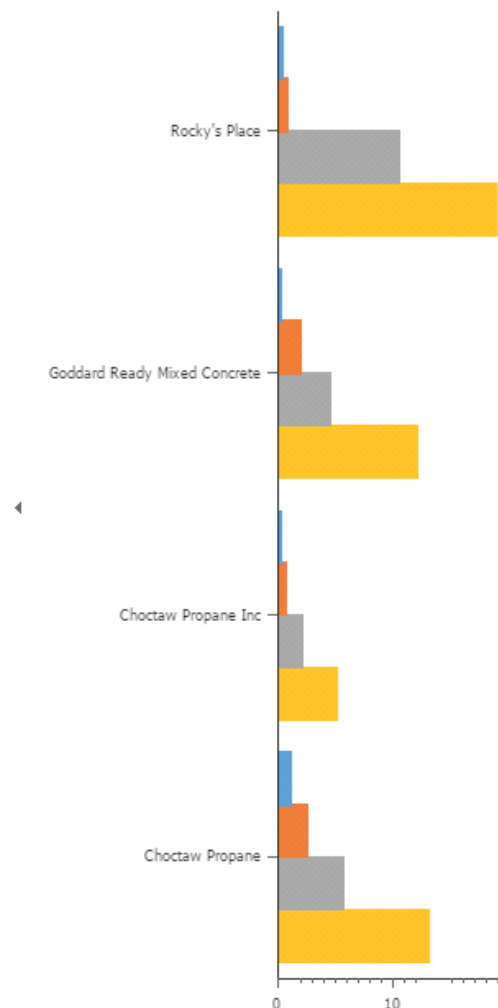
## Select

The select tool allows the user to draw a rectangle, circle, or polygon to select specific areas of interest for further investigation using the attribute table[1].   When you select specific sites, you can then run simple statistics on those areas of interest within the attribute table (more on that below).



## Search



The search tool simply allows the user to input a location to relocate the map extent.  The user could search for a city, zip code, address, etc…

---

[1] The chart tool contains a separate selection tool.

## Basemap

The basemap tool is used to select the background for the map extent. The default is aerial imagery with labels, but many other options exist such as road maps, topographic maps, and various others, as shown in the figure to the right.
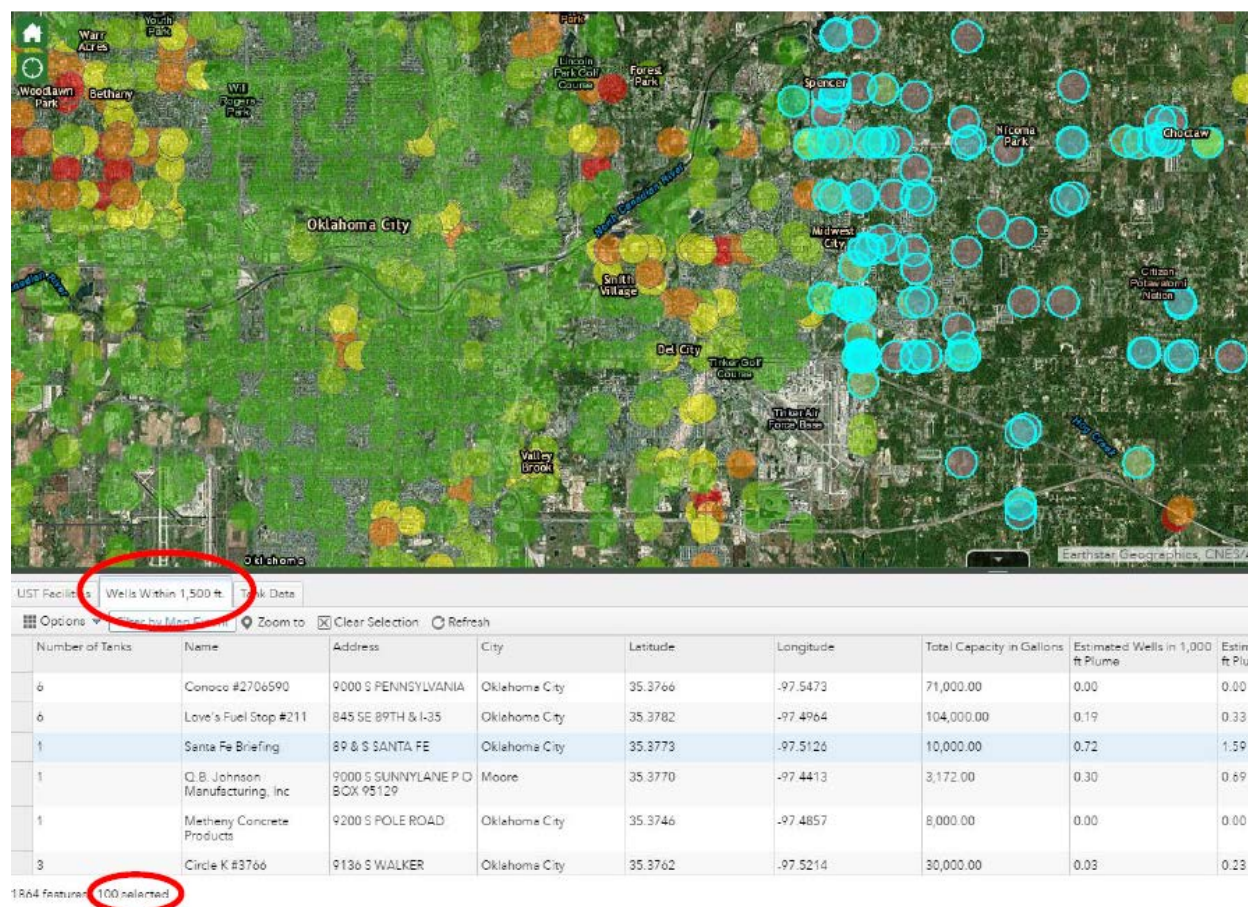


Basemap Gallery

## Attribute Table

The attribute table allows the user to dive deeper into the information on specific facilities and individual tanks. When the application is opened, the attribute initially appears at the bottom of the screen. It can be hidden or expanded by clicking the arrow at the top of the table. There are two tables that are associated with operational layers; "UST Facilities" and "Wells within 1500 ft" A third table is the individual tank data which is a relational database connected to both of the other two operation layers. Essentially the tables for facilities and wells within 1500 ft are the same and are both there for convenience when selecting from different layers. The select tool is ideal to use in conjunction with the attribute table and will allow a closer look at specific areas of interest.

Example:

As an end user if you spot a cluster of highly vulnerable areas (red) to the east of Oklahoma City (pictured to the right), the select tool enables you to draw a polygon around a specific area to conduct a more in-depth analysis on a specific area of interest.





| Number of Tanks | Name | Address | City | Latitude | Longitude | Total Capacity in Gallons | Estimated Wells in 1,000 ft Plume | Estima ft Plum |
|---|---|---|---|---|---|---|---|---|
| 6 | Conoco #2706590 | 9000 S PENNSYLVANIA | Oklahoma City | 35.3766 | -97.5473 | 71,000.00 | 0.00 | 0.00 |
| 6 | Love's Fuel Stop #211 | 845 SE 89TH & I-35 | Oklahoma City | 35.3782 | -97.4964 | 104,000.00 | 0.19 | 0.33 |
| 1 | Santa Fe Briefing | 89 & S SANTA FE | Oklahoma City | 35.3773 | -97.5126 | 10,000.00 | 0.72 | 1.59 |
| 1 | O.B. Johnson Manufacturing, Inc | 9000 S SUNNYLANE P O BOX 95129 | Moore | 35.3770 | -97.4413 | 3,172.00 | 0.30 | 0.69 |
| 1 | Metheny Concrete Products | 9200 S POLE ROAD | Oklahoma City | 35.3746 | -97.4857 | 8,000.00 | 0.00 | 0.00 |
| 3 | Circle K #3766 | 9136 S WALKER | Oklahoma City | 35.3762 | -97.5214 | 30,000.00 | 0.03 | 0.23 |

1864 features  100 selected

In the figure above, we see that we have selected 100 features from the "Wells within 1500 ft" layer, which are now colored light blue. When we click on the wells within 1500 ft tab in the attribute table we see the number of selected features in the bottom left corner. To show only the selected records in the attribute table, click the options drop down and then "Show selected records."

The selected records then appear in the attribute table as highlighted rows (see below). Each row represents a single facility with either 1 or more USTs on site. You can now run simple statistics on these facilities which represent our defined area of interest by clicking on the title of any column and clicking "statistics".



This will bring up the statistics window for the specified column (in this case total estimated wells within 1500 ft of a facility, see below). This shows that there are an estimated 4,019 domestic wells closer than 1500 ft to a UST facility within our area of interest. There are facilities that have no wells within 1500 ft, but on average (for this area) there are an estimated forty wells within 1500 ft of each facility. The maximum estimated wells within 1500 ft of a single facility in this area is 135. Running statistics again on the column labeled "Total Capacity in Gallons" you see that this area has a total storage capacity of 1.74 million gallons with an average tank capacity of 17,450 gallons.

Statistics

Field : Estimated Wells in 1,500 ft Buffer

| | |
|---|---|
| Number of Values | 100 |
| Sum of Values | 4,019.36 |
| Minimum | 0.02 |
| Maximum | 135.04 |
| Average | 40.19 |
| Standard Deviation | 25.56 |

OK

To take it one step further, you can use the filter option (also under the options tab) and create an expression to refine the results so we only see active facilities:

Click OK, and we see that only 44 of our previously selected 100 facilities are still active. We can create a second filter to refine it further to only those sites that have been confirmed to have had a leaking tank:



We now have 17 active facilities that have been classified as LUST sites. **Note** that when you use the filter option in the attribute table, the map extent will be updated to only show those sites that satisfy your filter expression. As you add filter expressions, tank sites that do not satisfy the expressions are removed from the visible map. Likewise, the selected records in the attribute table will also be removed so that the only viewable records are those that you originally selected that also satisfy the filter expressions.

Pre-Filter

Post-Filter
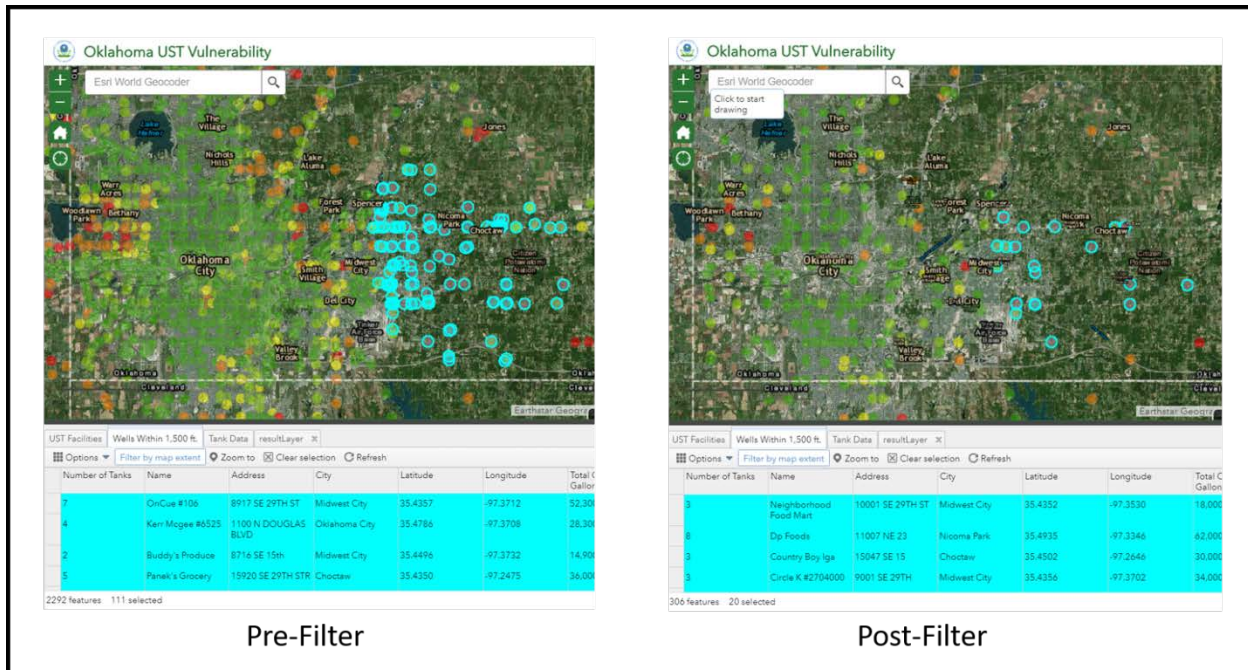
## Relational Tables

Information on specific facilities is available from the attribute table. With any number of rows selected in either the "UST Facilities" or "Wells within 1500 ft" table, click options (top left of attribute table) and then click "Show Related Records."  You will notice the attribute table tab switch to "Tank Data" and the records shown represent the individual tanks at each of the sites from your previous selection.  You will then be able to see how many active and inactive tanks each facility has and what their capacities are as well as what type of fuel they contain "Gasoline / Diesel / E-85 etc…).

## Quickly using the map to find information

Simply clicking on the map leads quickly to information from either the "UST Facilities" layer or the "Wells within 1500 ft" layer. This brings up a pop-up window showing relevant information on the selected facility. The image to the right shows this specific facility has 3 Underground Storage Tanks, is an active facility and is a LUST site.

Click on "Tank Data" under the Related Tables heading. This brings up a list of the three tanks. Click the "..." symbol in the bottom right and then select "View in attribute table." This shows the information for each of the three tanks in the attribute table. We find that the three tanks at this gas station all hold gasoline. Two tanks have a capacity of 12,000 gallons and the other has a capacity of 10,000 gallons. All three tanks are classified as currently in use and having leaked at some point. This particular gas station has roughly 30 domestic wells estimated to be within 1500 feet of the facility.
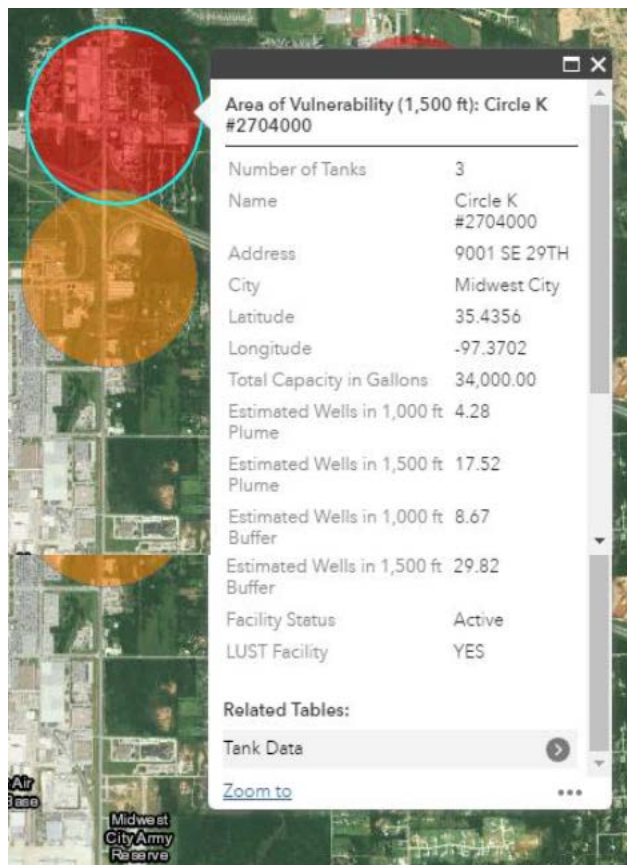


## Single-Tank Analysis

Where there is a lack of publicly available information giving the locations of all underground storage tanks, the APP user may define a single tank location. The process involves three steps; (1) defining a location, (2) setting the potential impact distance, and (3) calculating the estimated number of wells within the defined potential impact distance.

**Defining a Location**

Defining a specific location is accomplished by using the draw tool with the 'point' draw mode and clicking a point on the map. It is possible to select more than one location at a time, however, the time the analysis takes to run will increase with each additional location. It is recommended to use one location at a time.
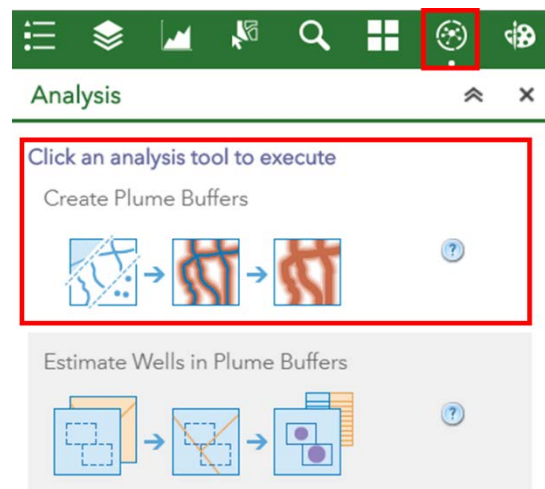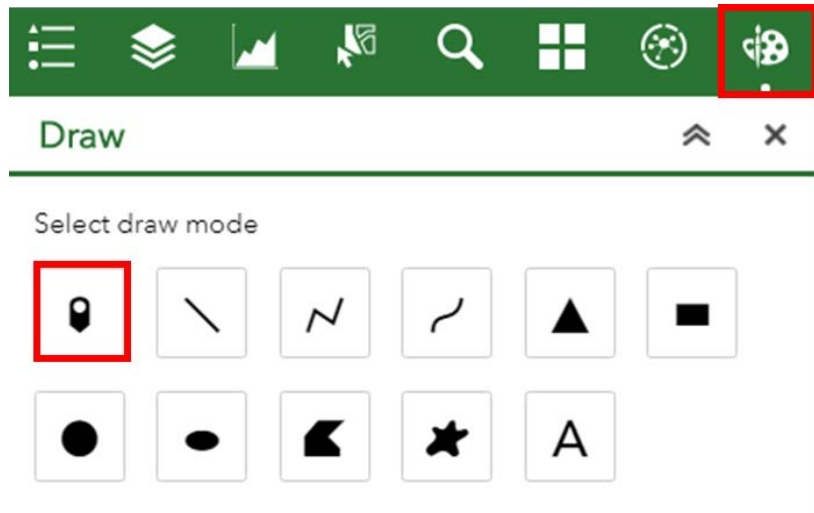


**Setting Potential Impact Distance**



After having chosen a distance for delineation of the potential impact zone according to considerations given in "Appendix A: Assessment of Plume Extents" or by agency policy (i.e., 1000 ft), the selected distance is entered. With a location defined by the selected point, the 'Create Plume Buffers' tool (within the Analysis tool set) is used to create a potential vulnerability area for the tank.

By default, the selection for (1) "Choose layer containing features to buffer" should be set to "Points" which is a reference to the user defined location in the previous step. (2) "Enter buffer size" is set to define the radius of potential impact zone (3) Finally 'Result layer name' is used to designate the resulting layer (4) Select 'Run Analysis'.

## Calculate Estimated Number of Domestic Wells

## Within the Potential Impact Distance

The 'Estimate Wells in Plume Buffers' tool allows the user to calculate the estimated number of wells within the area that was created from the previous step (Setting Potential Impact Distance). 'bufferLayer' will be the input for (1), regardless of what you named the output from the 'Create Plume Buffer' tool. The layer to summarize is 'Wells', (3), allows the user to calculate statistics for the defined area of vulnerability. In this example we include total estimated domestic wells (Est_Wells), estimated population, and estimated housing units. Leave (4) as the default. Give your output a unique name (5). Run the analysis.

The result will be a circular area drawn around the selected point. The name of the layer will, by default, appear as 'resultLayer' and can be seen in the legend. Clicking on the map in the defined area will display a pop-up box with the results. You may need to click the right-facing arrow in the top right corner of the pop-up box to view the correct layer data. The pop-up box will then display the calculated area of the potential impact area, the estimated wells, housing units and population. In this case, we estimate there to be 53 wells, 251 housing units and a population of 520.
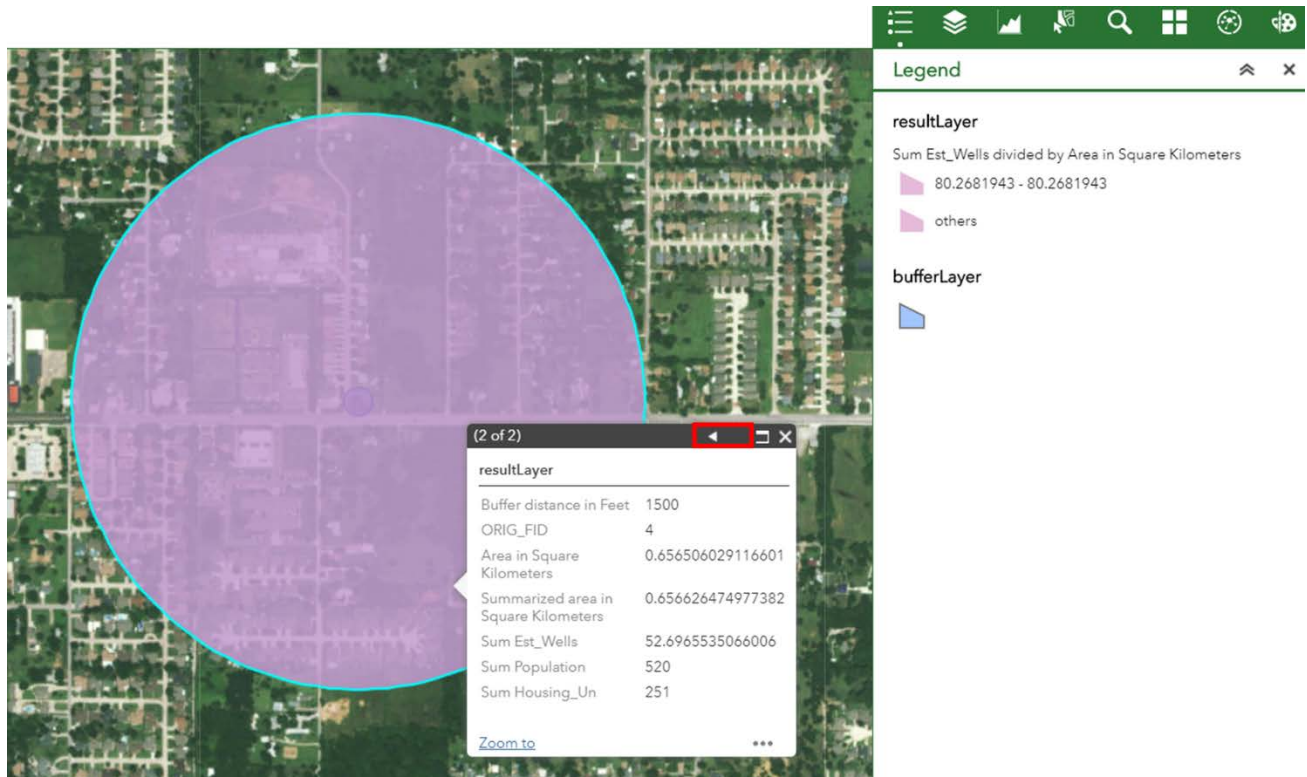
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# Appendix A: Assessment of Plume Extents

## Length of BTEX Plumes

Studies of the length of contaminant plumes indicate the expected extent of contamination from leaking underground storage tank sites (API, 1998, Connor et al., 2015). Although based on limited data, these studies indicate that the maximum observed extent of contaminant plumes is on the order of 1500 ft (500m).

For confirmation of these distances, analytical models of ground water transport were constructed in Java, and consisted of one- and two-dimensional analytical solutions (van Genuchten, 1981, Batu and van Genuchten, 1990) . To account for transport of benzene, a carcinogen, an initial concentration of 5.0 mg/L was selected as a baseline case. For comparison and exploration of the effect of source concentration on plume length, simulations were also made for source concentration of 0.5, 1.0, 25.0 mg/L. The plume extent was taken as the drinking water maximum contaminant level (MCL) of 0.005 mg/L. Thus the plume extent consists of all the water contaminated at levels above the MCL. The initial concentration, 5 mg/L, was selected as it is in the range of concentrations associated with fresh gasoline (Weaver, 2004).

 Several scenarios were simulated with parameters typical of leaking underground storage tank sites (Table 1). Most important of these were varying conductivity of subsurface materials, dispersivity, and biodegradation rates. The material types range from tight clays to highly conductive sands and gravel. In each case the gradient was assumed to be 1/1000. The dispersivities were chosen to correspond to the data tabulation of Gehlar et al. (1992) and the weighted regression to those data developed by Xu and Eckstein (1995). At a scale of about 3,000 ft (1000 m), the Xu and Eckstein (1995) regression result is about 10 m and higher estimates of 100 m (one-tenth the plume length) were used (Figure 3). Note that the data at this scale were judged to be of low reliability, and that conservative tracer experiments were used to generate the results. The plume estimates from the analytical solutions are constrained by the chosen end point of 0.005 mg/L. Actually these plumes, even considering biodegradation, would be longer as concentrations exist below the threshold concentration of concern. The biodegradation rates were determined from 365 and 730 day half-lives. The source width was taken as 100 m for the two-dimensional model. The effects of conductivity, half-life and dispersivity on plume length are summarized in the following sections.

**Table 1  Parameter values used in simulation.**

| Conductivity (m/d) | Dispersivity (m) | Half Life (d) |
|---|---|---|
| | *Sand, Gravel* | |
| 86.4 | 10 | 365 |
| | | 730 |
| | 100 | 365 |
| | | 730 |
| | 200 | 365 |
| | | 730 |
| | *Silt, Silty Sand* | |
| 0.864 | 10 | 365 |
| | | 730 |
| | 100 | 365 |
| | | 730 |
| | 200 | 365 |
| | | 730 |
| | *Clay , Glacial Till* | |
| 0.00864 | 10 | 365 |
| | | 730 |
| | 100 | 365 |
| | | 730 |
| | 200 | 365 |
| | | 730 |



Gelhar, Welty and Rehfeldt (1992) Dispersivity Data
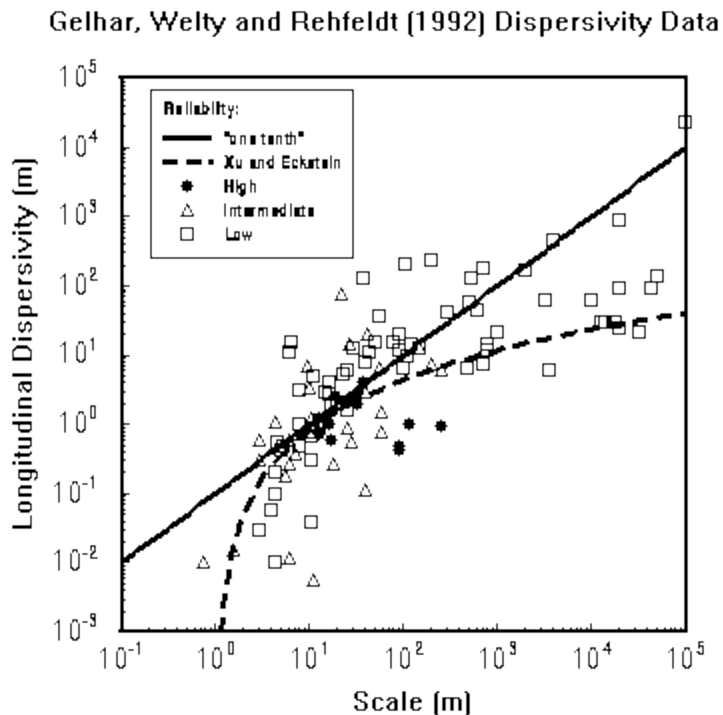
Figure 3.  Longitudinal dispersivity data from Gelhar et al. (1992) plotted against "1/10" of length scale, and the weighted regression formula of Xu and Eckstein, 1995.  Most of the reliable data were at plume scales of 10 to 100 m.

## Summary of Simulations

### Conductivity

In one dimension, plume length increased with increasing conductivity and was proportional to the order of magnitude of conductivity increase (Figure 4). The plume in the most conductive material (sand and gravel) expanded for about 2700 days and peaked at a distance of about 1100 ft (335 m). The plume in least conductive soil (clay and glacial till) also expanded for 2700 days but peaked at distance at about 2 ft (0.6 m).   Only small differences were found between the one- and two-dimensional results, presumably due to biodegradation and the width of the source.
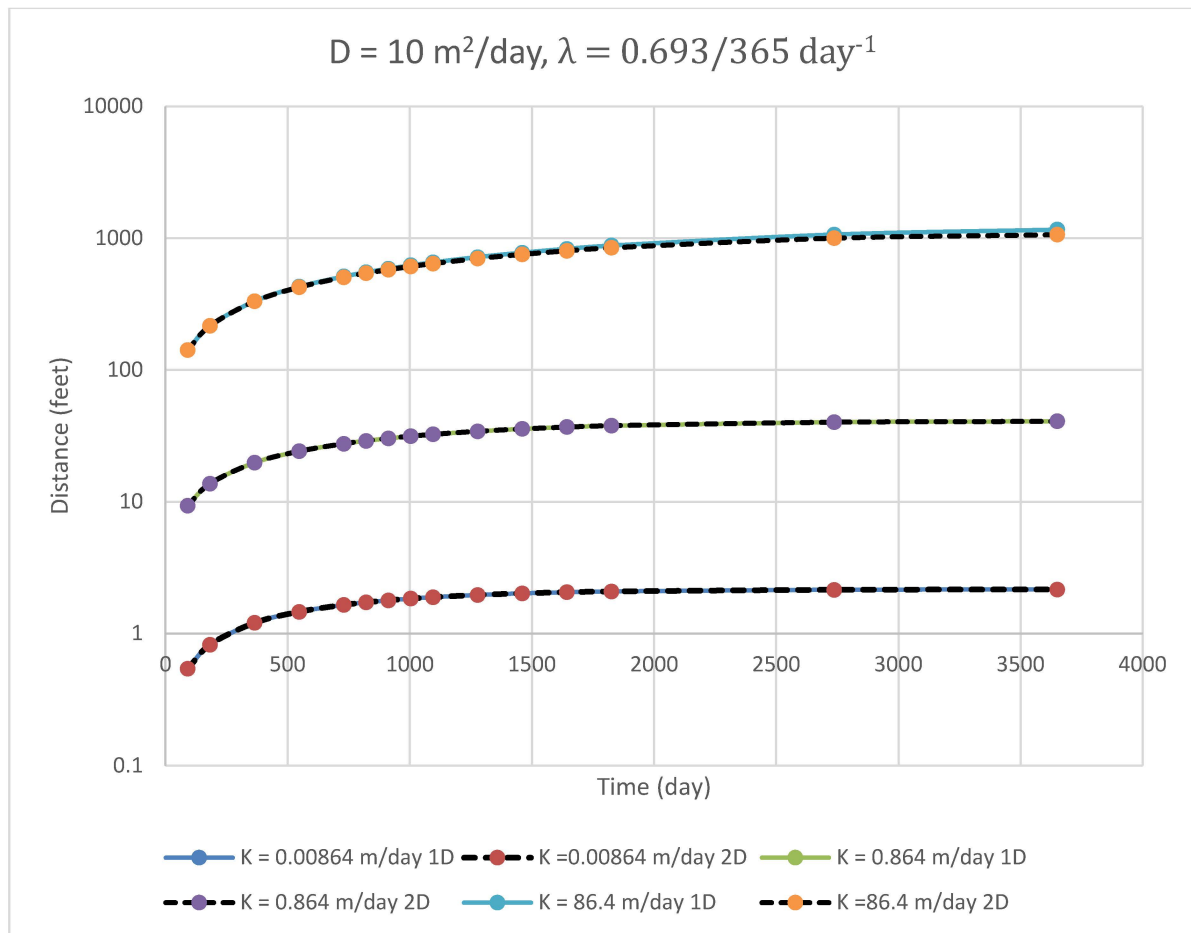


Figure 4.  Plume lengths at different conductivities

## Dispersivity

The plume length also increased with the dispersivity (Figure 5). The plume with disperisivity of 10 m²/day extended to distance of 1160 ft (350 m) and plume with dispersitivity of 200 m²/day extended to distance of 2,300 ft (700 m). At lower longitudinal dispersivity, small differences are evident between the one- and two-dimensional results. In the two-dimensional model, mass transport occurs lateral to flow, and less mass is transported longitudinally; thus the 2D model result has a lower plume extent than the 1D result.
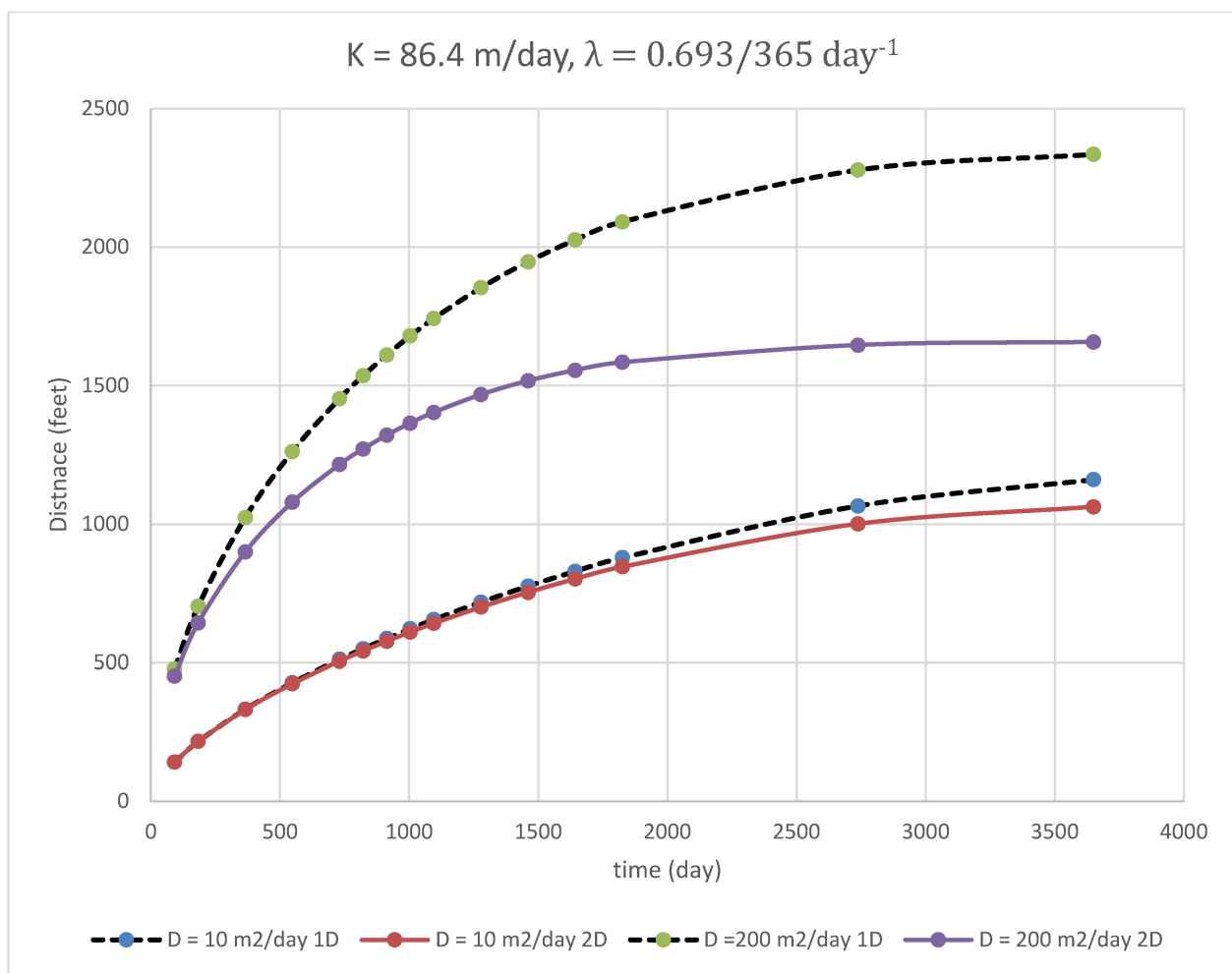


Figure 5. Plume lengths at different dispersivities.

## Biological Degradation (Half-life)

Longer half-life corresponds to lower biological degradation rate, so the plume lengths are greater when longer half-lives are selected (Figure 6). A plume extended up to 1200 ft (350 m) at half-life of 365 days and the plume extended to 1600 ft (490 m) at half-life of 730 days, when all other parameters were the same. Similar results were obtained in either one- or two-dimensional simulations.
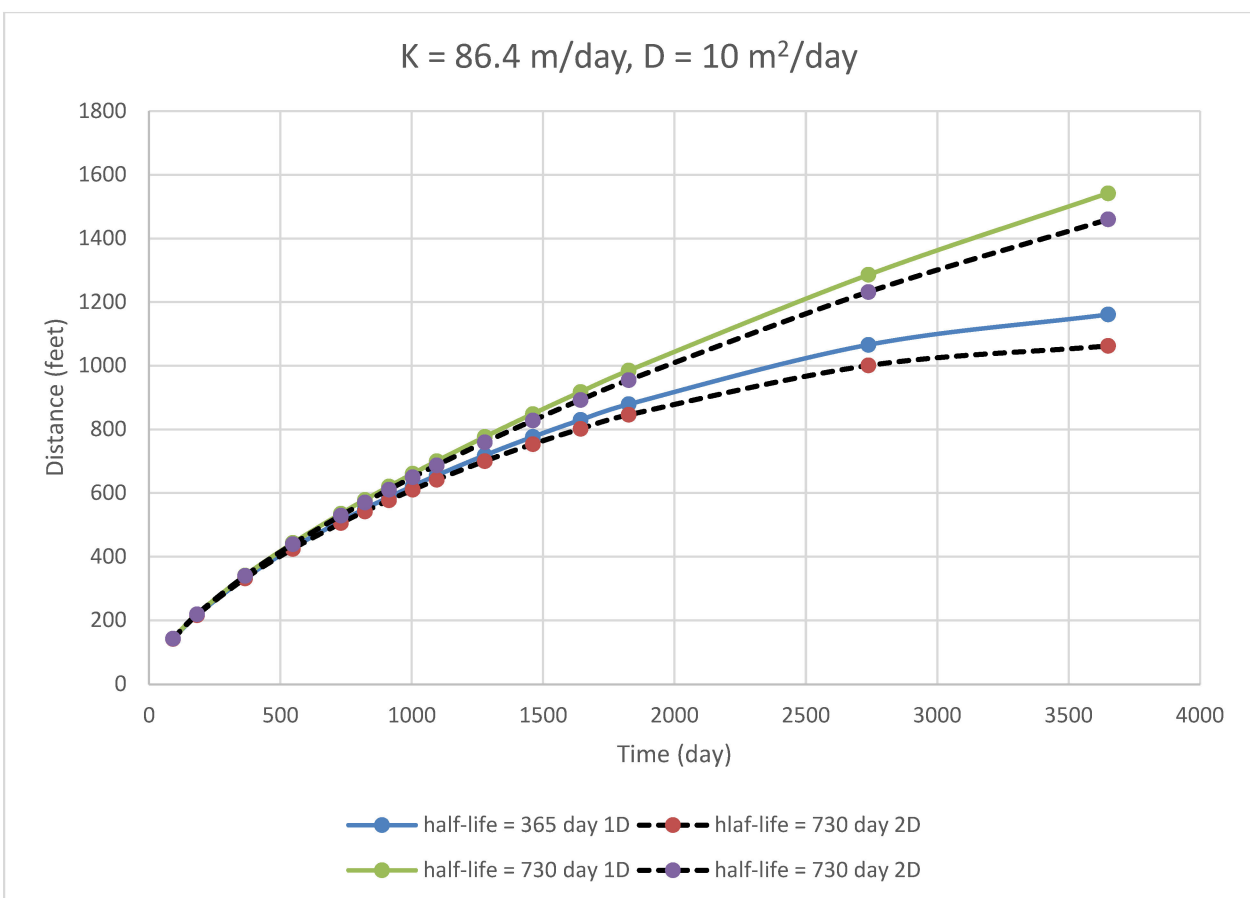


Figure 6. The plume length at different biological degradation rate.

**Effect of Source Concentration on Plume Length**

Although the plume length depends on source concentration, the dependence is mild. For simulations with source concentrations of 0.5 to 25 mg/L, the plume length increased by a factor of 2.6. Notably the increase in source concentration was a factor of 50, indicating that changes in source concentration are dampened by the model when the results are expressed as plume length.

$$K = 86.4 \, \text{m/day}, \lambda = 0.693/365 \, \text{day}^{-1}, D = 200 \, \text{m}^2/\text{day}$$

Figure 7. The effect of changing source concentration (Co) on plume length.

**Retraction of Plumes**

Because of biodegradation and dispersion, the maximum extent of plumes may retract. This is demonstrated both through modeling and through the empirical data analysis of Connor et al. (2015). Simulations were conducted with an exponentially-decaying flux source (solution C14 of van Genuchten,

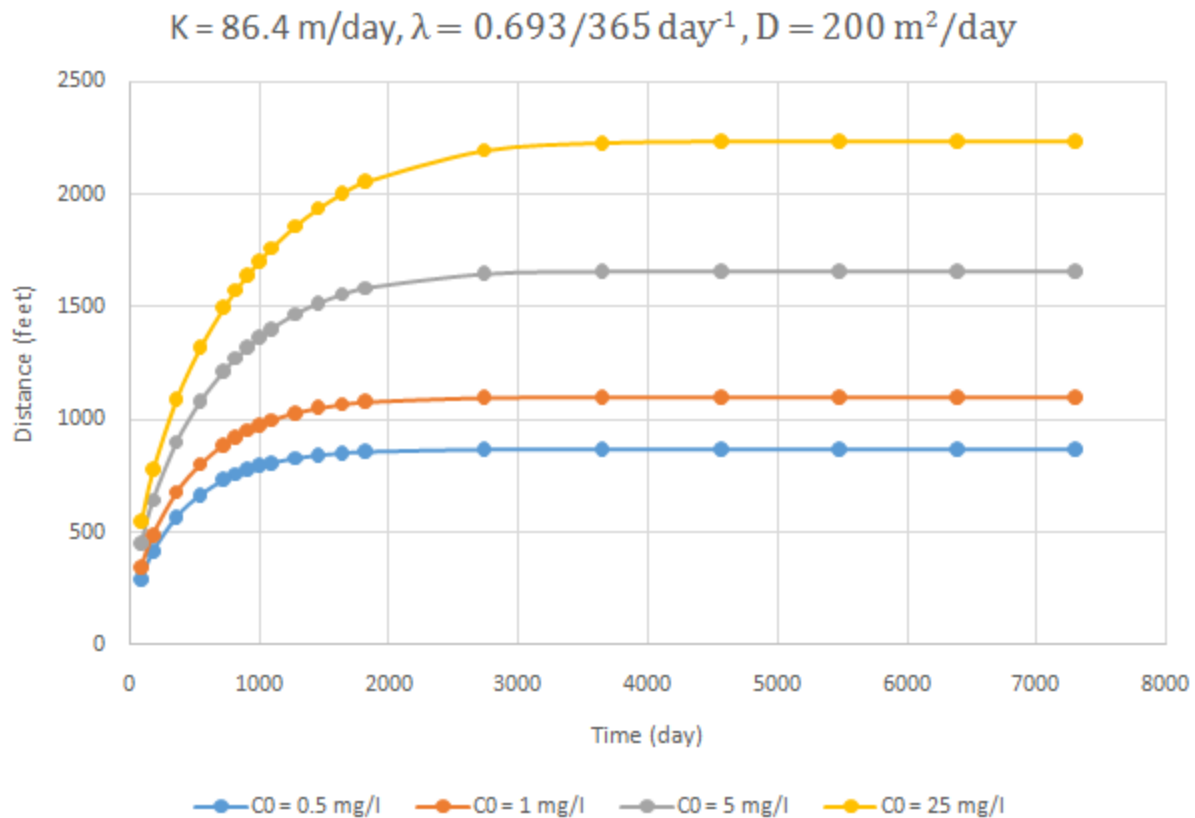1981)  used rates of source depletion, expressed as half-lives of 1 year, 2 year, 3 year and 5 years[2].  As before, a gradient of 1/1000 was assumed, and a dispersivity of 10m²/day was used. The biodegradation half-life of 1.1 yr was used for the contaminant in ground water. The plumes contracted soonest for lowest source half-lives, which are the least persistent sources (Figure **8** to Figure **10**).



Figure 8.  Extent of contaminant plume as defined by 0.005 mg/L concentration showing plume retraction in low conductivity aquifer material.  (Solution C14 of van Genuchten (1981), dispersivity of 10 m, and biodegradation half-life of 1.1 year).

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[2] Simulations with low source half-life values (1 year) and low conductivities (0.00864 m/day, 0.864 m/day) did not converge to a solution, presumably indicating that no contaminant plume forms under these conditions.

Figure 9.  Extent of contaminant plume as defined by 0.005 mg/L concentration showing plume retraction in moderately conductive aquifer material.  (Solution C14 of van Genuchten (1981), dispersivity of 10 m, and biodegradation half-life of 1.1 year).
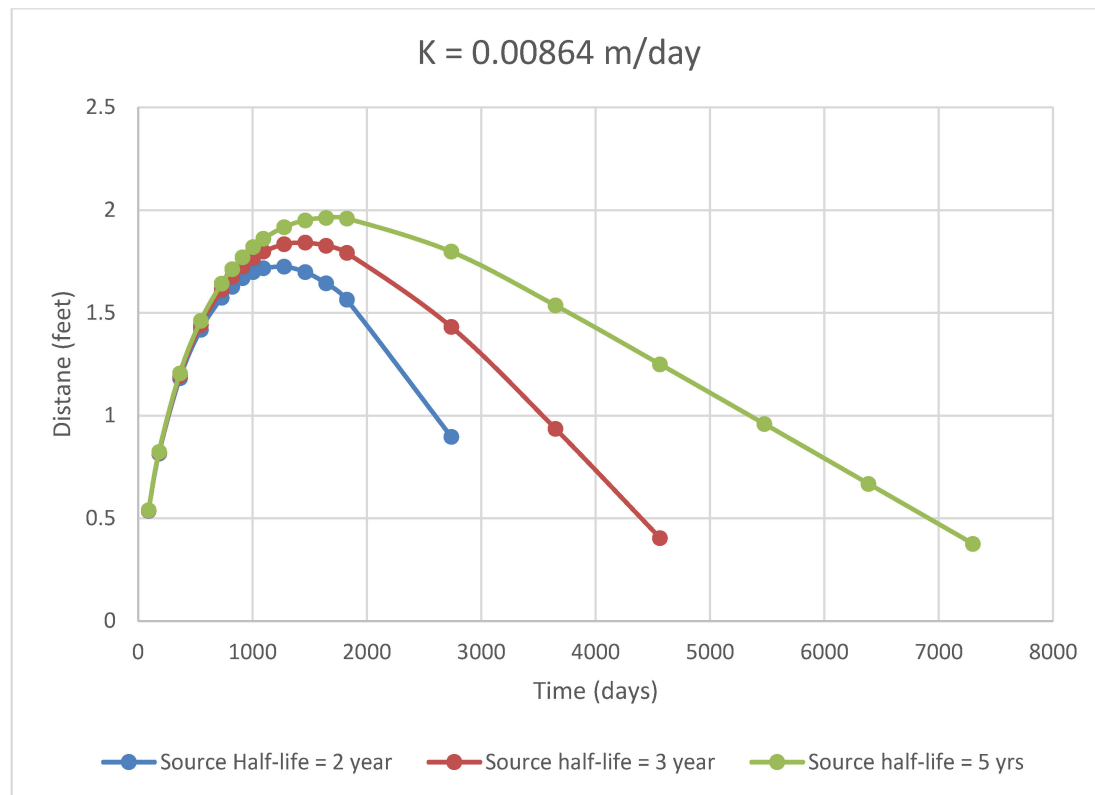
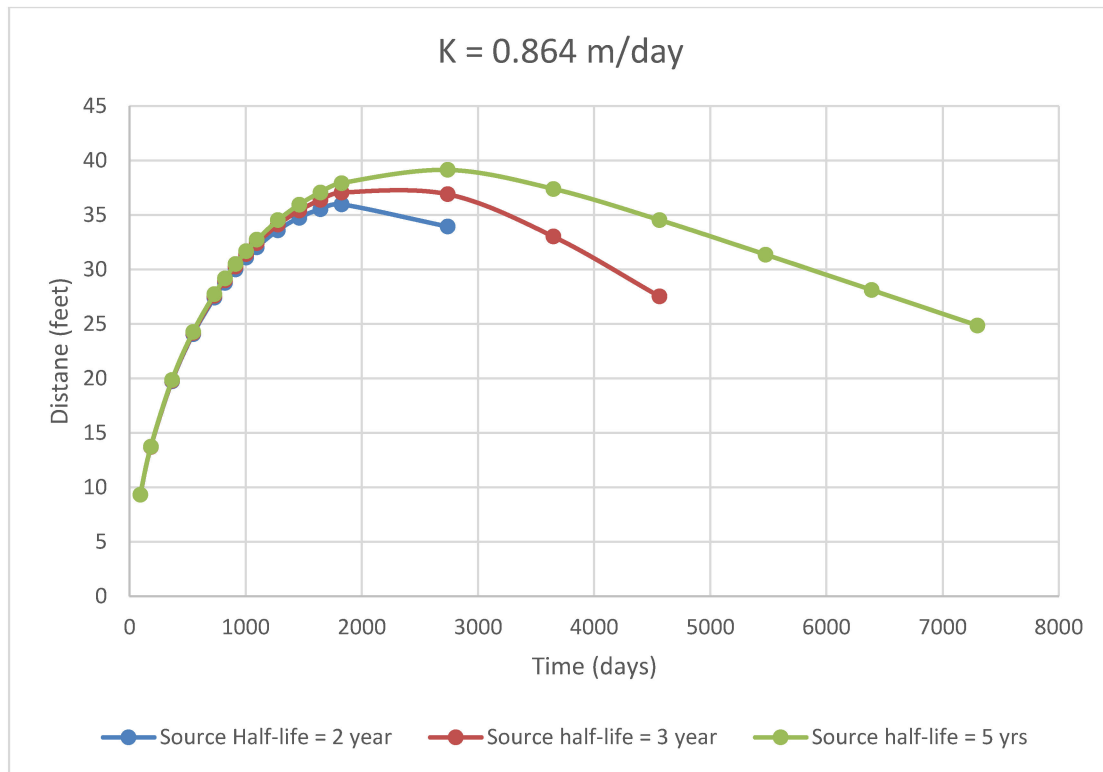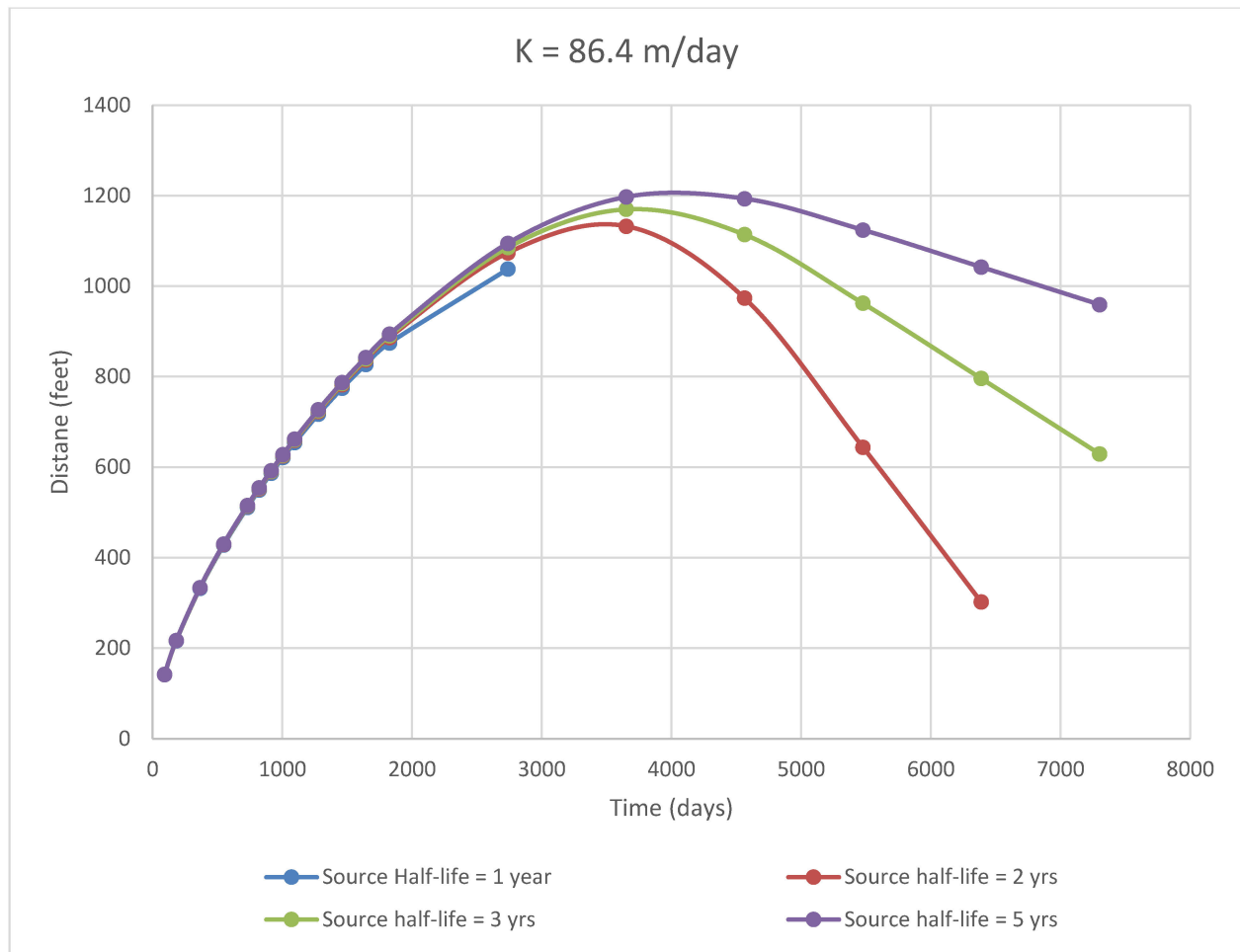Figure 10.  Extent of contaminant plume as defined by 0.005 mg/L concentration showing plume retraction in highly conductive aquifer material.  (Solution C14 of van Genuchten (1981) , dispersivity of 10 m, and biodegradation half-life of 1.1 year).

# Result Summary

As shown above, the model solutions were highly dependent on the combination of parameters. The plume length extended up to 3,810 ft (1160 m) under the most favorable conditions (most conductive soil, dispersivity of 200 $m^2$/day, and half-life of 730 days). Conversely, plume lengths of only a few feet were observed in case of the least conductive soils.

The study by Connor et al. (2015) compiled data from over 1,300 plumes of Benzene, 500 plumes of methyl tert-butyl ether (MTBE) and 108 Plumes of tert-butyl Alcohol (TBA). They concluded that most of the Benzene and MTBE plume lengths stabilized between 425 and 530 feet at concentration of 5 µg/L. The TBA plumes were comparable in length to the benzene and MTBE plumes. They observed that plumes with lengths in excess of 1000 feet were extremely rare. The authors acknowledge, however, that at many leaking underground storage tank sites ground water plumes are incompletely characterized because of various limitations on sampling.

The results of the modeling study performed for this paper show that longer plumes are theoretically possible if the hydraulic parameters of the porous media are favorable, and biodegradation rates are low. However, these are not supported by field evidence, and the plume length is highly dependent on the choice of parameters. Dispersion, in particular, has orders of magnitude variability for conservative tracers, and was picked arbitrarily for the modeling study. Hence, for planning purposes a maximum plume length of 1000 to 1500 ft has been found reasonable by several states as it encompasses the known distribution of plume lengths.

# Appendix B: Implementation Details

## Summary

The toolbox for the APP consists of three separate tools which will allow an end user to input a point layer representing the locations of LUST sites and a flow direction raster (easily created in most GIS software packages). The following describes the various tools.

This set of tools takes the locations of LUST sites and determines the generalized ground water flow direction away from the tank site based on a flow direction raster, which is created separately prior to using this toolset. This approach is based on the premise that ground water flow mimics the surface topography. Because of a number of factors, the actual ground water flow direction may differ from that predicted from surface topography. These factors (primarily pumping from wells and subsurface heterogeneity, impervious surface cover redirecting runoff) require site-specific analysis and investigation. Thus, the results from the transport tool are presented as a first approximation which requires further site-specific data collection, which is likely to require field sampling.

In addition to the physical effects, the outcomes of this toolset are heavily dependent on the input flow direction raster. Generally, flow direction rasters are created by defining the direction of steepest dropoff from an origin cell to the neighboring 8 cells (termed "queen connectivity"). The simplest form of this is called an 8 directional (D8) flow raster which will always return one of eight possible directional values (increments of 45 degrees). This is the type of flow direction raster that is created by using the flow direction tool in ArcGIS. The other, higher resolution option is called an infinite direction (D-Infinity) flow raster. A D-infinity flow direction raster will determine the steepest dropoff from the origin cell by determining the neighboring pair of cells that represent the steepest slope and then calculating an angle between those two cells based on their proportional difference. One such example of a D-infinity flow direction tool is freely and publicly available from the hydrology lab of David Tarboton at Utah State University (http://hydrology.usu.edu/taudem/taudem5/index.html), and is described as:

"Assigns a flow direction based on the D-infinity flow method using the steepest slope of a triangular facet (Tarboton, 1997, "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," Water Resources Research, 33(2): 309-319). Flow direction is defined as steepest downward slope on planar triangular facets on a block centered grid. Flow direction is encoded as an angle in radians counter-clockwise from east as a continuous (floating point) quantity between 0 and 2 pi. The flow direction angle is determined as the direction of the steepest downward slope on the eight triangular facets formed in a 3 x 3 grid cell window centered on the grid cell of interest. The resulting flow in a grid is then usually interpreted as being proportioned between the two neighboring cells that define the triangular facet with the steepest downward slope."

The LUST Plume Locations toolbox has three separate steps. The two important steps are "Assign Plume Variables" which takes point locations and creates the necessary data that will be used to create plumes based on desired plume distance and angular flow variables, and "Points to Plumes" which creates the actual plume areas based on the input variables from the previous step. These tools are provided separately to increase efficiency and decrease computational time. The third tool, "ESRI Flow Direction to Radians", converts an esri flow direction raster into radians from east which will enable the "Assign Plume Variables" tool to accept it as an input.

## Tools
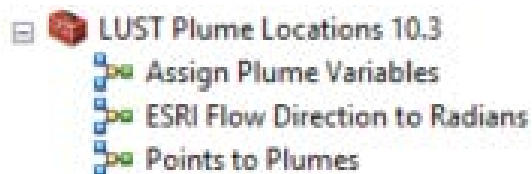


1. ESRI Flow Direction to Radians:

   This tool is only necessary if the flow direction raster you intend to use is the output from the "Flow Direction" tool in ArcMAP. It is encouraged that a D-infinity flow direction raster is used in order to maximize accuracy. As noted above, a tool that is ready to use in ArcGIS is available from TauDEM at Utah State University. QGIS, a well-known open source GIS software package also offers a D-infinity flow direction tool.



**ESRI Flow Direction to Radians**

Converts the output of an ESRI flow direction raster into Radians (from east)
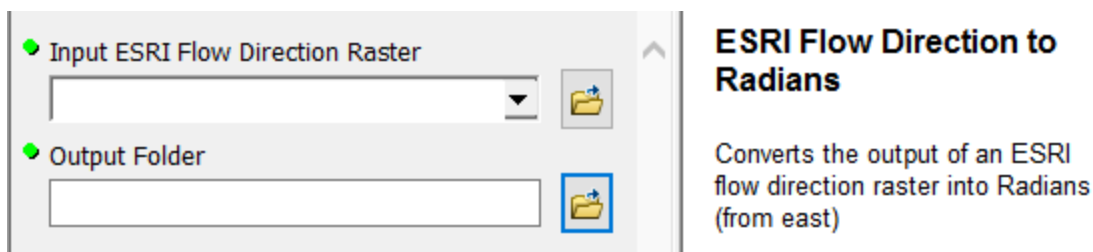
2. Assign Plume Variables:

   This tool prepares the point layer to be used in the 'Points to Plumes' tool.
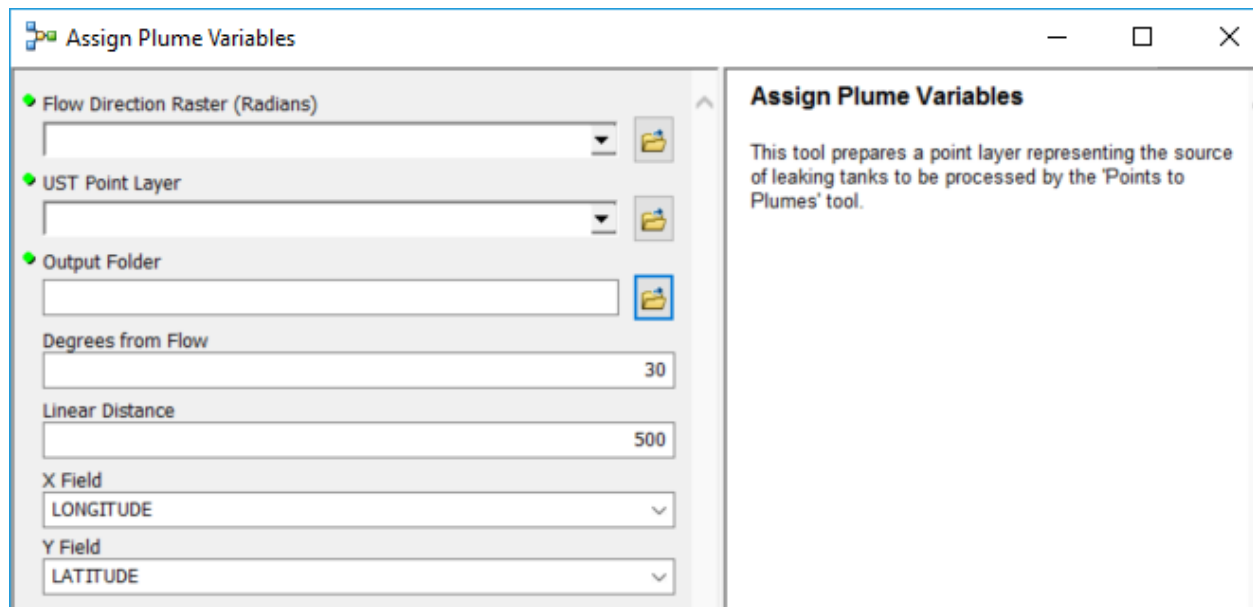
The two files needed as inputs are the flow direction raster (in radians from east) and a point layer representing the locations of underground storage tanks. The point layer for tanks must also have a unique id field, as well as XY coordinate fields, which must be labeled in the appropriate boxes. The maximum distance and angle of flow for the plume must be determined. An annotated graphic of the tool is available on the following page. The steps this tool cycles through are as follows (A – E):

A. Extract the values from the flow direction raster to the points representing the locations of the leaking underground storage tanks. Every point location now has a direction (in radians) of steepest path.

B. Add fields to the point layer representing flow direction (in degrees), left bounded angle (in degrees), and right bounded angle (in degrees). These fields will be populated in the next steps.

C. Calculate the angle of steepest flow (in degrees) by converting radians to degrees, this will populate one of the fields just created.

D. Calculate the remaining two empty fields (left and right bounded angles). This step is a bit tricky since, if you are calculating degrees difference from the steepest path, you could end up with degree values <0 or >360. Therefore, this step calculates the left and right bounding angles by adding or subtracting the plume angle input from the value of the direction of steepest path. It then isolates any values less than 0 or greater than 360 and corrects them. Ex: -15 becomes 345, and 380 becomes 20. At this point, each tank point now has fields representing the angle of steepest flow, and the direction of the left and right bounding lines representing the specified angle of the plume.

E.   The final step is to write the output point file so that it may be input into the 'points to plumes' tool and to write an empty feature class that will hold the results of the plume to points tool.  When the points to plumes tool runs, it will iterate through each tank site separately and append each result to this empty dataset.

3.   Points to Plumes

The points to plumes tool takes the prepared point layer and iterates through it to build polygons that represent the estimated maximum plume area for leaking tanks based on given directions and angles.  The steps this tool uses are described below (A to F.)

A.   Iterate through feature selection.  This tool runs an iteration for each individual tank site. This is necessary to avoid the clipping of overlapping polygons when the plume area is defined for each site.

B.   The 'Bearing distance to line' tool is called to create defined bounds for the plume.  The tool calls the max distance, and angle fields from each feature which were calculated in the previous tool.  Using trigonometry, the length of the sides of the triangle are calculated to run this tool.  The outputs are two separate (left and right) bounding lines. The output can be seen to the right, where purple represents the left bound and blue is the right bound.



C.   Once the bounding lines are in place, the start and end points of the bounding lines are converted into separate points, which results in a separate point feature with three points (the origin and two end points)
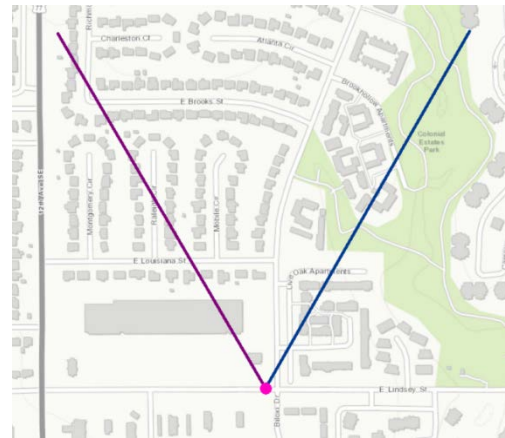
D.   The vertices are then converted into a polygon which represents the initial plume area, but because of the triangle shape of the plume, there are now areas that are within the plume area but farther than the defined maximum distance. When the bearing distance to line function was called, an input of 500 meters maximum distance at a 30 degree angle would actually yield a triangle side of 577 meters.
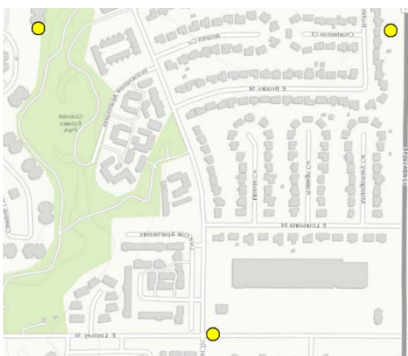


E. The initial plume area is clipped based on a separate buffer that was created based on the input values of maximum plume distance.  This will yield the cone shape so that all of the polygon area is within the designated area (i.e. 500 meters).
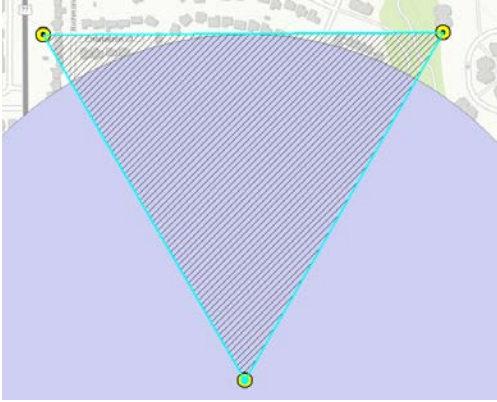
F.       Finally, a spatial join is run to reattach the original site attributes to the newly created polygon, allowing the end user to maintain site specific information (owner/LUST status/licensing/inspection etc…)