

An Approach for Developing Site-Specific Lateral and Vertical Inclusion Zones within which Structures Should be Evaluated for Petroleum Vapor Intrusion due to Releases of Motor Fuel from Underground Storage Tanks

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ABSTRACT

Buildings may be at risk from Petroleum Vapor Intrusion (PVI) when they overlie petroleum hydrocarbon contamination in the unsaturated zone or dissolved contamination in ground water. The U.S. EPA Office of Underground Storage Tanks (OUST) is preparing *Guidance for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites*. The OUST guidance provides general screening criteria that can be used to identify structures that are at risk from PVI. The criteria are used to determine if a structure is included within a lateral or vertical zone where proximity to the contaminant might make the building vulnerable to PVI. If the structure is within a lateral or vertical inclusion zone, then additional investigation is necessary to evaluate and manage exposure to the vapors.

This Issue Paper contains technical suggestions and recommendations proposed by the U.S. EPA Office of Research and Development for applying the criteria provided in the OUST guidance. The Issue paper provides a graphical approach to define a lateral inclusion zone based on the proximity of a structure to the presumed maximum extent of contamination. The presumed maximum extent of contamination is defined by a perimeter of clean monitoring locations that are arranged around the known source of contamination. The lateral inclusion zone is extended past the presumed maximum extent of contamination to allow for uncertainty of the concentrations of contaminants in the space between monitoring locations. The Issue Paper provides instructions and suggestions to use knowledge of ground water flow to refine the lateral exclusion zone, and reduce the area where additional investigation is necessary. The Issue Paper provides recommendations on collecting and analyzing core samples to determine the vertical extent of contamination in the unsaturated zone, and water samples to determine the extent of contamination in ground water. The Issue Paper provides illustrations of the appropriate comparison of the field data to the criteria in the OUST Guidance. In combination, definition of lateral and vertical inclusion zones makes the best use of site characterization data for assessing the risk of PVI to structures at a LUST site. The procedures

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outlined in this Issue Paper provide a realistic data-driven approach to screen buildings for vulnerability to PVI.

1.0 INTRODUCTION

Vapor intrusion is a process whereby vapors of hazardous substances move through unsaturated soil and enter buildings. Occupants of the buildings are exposed to the hazardous substances as vapors in indoor air. The vapors may originate from contaminated ground water or from light non-aqueous phase liquids (LNAPLs). Underground storage tanks (USTs) are regulated under Subtitle I of the Solid Waste Disposal Act. Most USTs are used to store motor fuel (e.g., gasoline, diesel fuel) that is composed primarily of petroleum hydrocarbons (PHCs). Releases of motor fuel from a leaking UST may result in generation of PHC vapors and can result in petroleum vapor intrusion (PVI).

The U.S. EPA is developing *Guidance for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites* (U.S. EPA, 2013a). The guidance provides general screening criteria that can be used to identify structures that are at risk from PVI. In general, structures are at risk from PVI when they overlie masses of residual LNAPL in the unsaturated zone, accumulations of liquid LNAPLs at the water table, or petroleum contamination dissolved in ground water at levels that have the potential to pose a risk to receptors through the vapor intrusion pathway.

The potential for human exposure from PVI may be limited because of the biodegradability of PHCs. The PVI Guidance provides recommended screening levels for petroleum constituents above which the potential for PVI should be considered. If the available data on the distribution of petroleum components in soil and ground water suggest a reasonable possibility that PVI may impact a structure, that structure is considered to be contained within an inclusion zone, which implies that additional investigation is necessary to evaluate and manage exposure to the vapors.

As discussed in detail later in this document, the inclusion zone considers both lateral and vertical proximity to the vapor source (i.e., mobile LNAPL, residual LNAPL, and dissolved contamination). All structures in the immediate vicinity of the source

area are first evaluated to determine if they are within the lateral inclusion zone. This approach logically follows the typical site investigation as it progresses over time from the source area outward in the direction of ground water flow to the edges of the dissolved plume. As more site-specific information is compiled, the extent of the inclusion zone may change. If any structure is within the lateral inclusion zone, then it is further evaluated to determine if it is in the vertical inclusion zone.

The lateral inclusion zone is discussed in Section 2. The vertical inclusion zone is discussed in Section 3. As described and illustrated in these sections, it may be necessary to acquire additional site characterization data before this approach can be used with confidence to screen structures and determine whether they are within the inclusion zone for PVI.

Both lateral and vertical inclusion zones should be delineated using site-specific data. A conceptual site model (CSM) that integrates all available data and information about a particular site should be developed and continually refined as new data become available. Especially near the beginning of an investigation at a leaking UST site, there is typically much uncertainty due to the lack of site-specific data and information. To compensate for uncertainty due to lack of data, the screening criteria produce a larger inclusion zone. As more data are integrated into the CSM, the degree of uncertainty progressively diminishes. Thus, the extent of the lateral inclusion zone can often be reduced. However, improved understanding necessarily takes time and resources.

If inhabited buildings or sites for future buildings are not located within one or the other of these inclusion zones, the vapor intrusion pathway may be considered to be incomplete and no further consideration of the pathway should be necessary for these buildings. This assumes that there are no preferential pathways for contaminant migration at the site. This also assumes that conditions at the site do not change. Factors to consider in deciding whether to exclude sites from further evaluation of PVI may include future land use, construction of utility trenches through or near previous contamination, increased ground water usage that might change the direction of ground water flow, and additional releases of contaminants.

This Issue Paper contains technical suggestions and recommendations proposed by the U.S. EPA Office of Research and Development for applying the criteria provided in OUST's PVI Guidance (U.S. EPA, 2013a). The material in this Issue Paper is not guidance from the U.S. EPA Office of Underground Storage Tanks (OUST).

The federal UST program delegates authority to implement an UST program to the states. Most of the state agencies use a risk based approach to manage vapor intrusion of PHCs and other fuel constituents (U.S. EPA 1995, 2002). The staff of the state agencies or the Indian nations that implement the UST program may choose to implement another approach to apply screening criteria recommended by U.S. EPA (2013a). If they choose to implement this approach, they may modify this approach to make it more appropriate to their particular needs.

2.0 THE LATERAL INCLUSION ZONE

This section discusses methods to determine whether proximity of a structure to a source of contamination puts the structure at risk for PVI. Contamination can be mobile LNAPL, residual LNAPL, or a dissolved plume. It is important to define a lateral inclusion zone based on the separation distance between the structure and monitoring locations that are known to be clean instead of the distance from known contamination. This is especially critical if the extent of subsurface contamination is not well-defined, as there is no way to know how far the contaminated material actually extends from the source of contamination toward the receptor.

Typically at the beginning of a leaking UST investigation the full extent and location of contamination and the direction of ground water flow are not well-defined. An illustration of these uncertainties is presented in Figure 1. Here a leaking UST has impacted the five monitoring wells initially installed to assess the extent of contamination. Because all of the wells are contaminated, the actual extent of contamination cannot be determined. Because sufficient ground water monitoring data have not yet been collected, the direction of ground water flow has not been determined. Given the uncertainty in the direction of ground water flow, a contaminant plume could

conceivably migrate away from the source in a variety of directions as shown.

The procedure described to define the lateral inclusion zone is based on the assumption that the closer together the monitoring points, the less uncertainty there is about the extent and location of contamination. Conversely, with fewer monitoring points spaced farther apart the uncertainty is greater. As monitoring points are placed closer together and additional monitoring points are installed to fill in the gaps in the monitoring network, the extent of contamination is determined more accurately. This concept is depicted schematically in Figure 2, which shows a simplified relationship between the location of clean monitoring points and the extent of contamination. In this example, contamination extends from leaking USTs in the direction of a potential receptor, which has been established by determining the ground water flow direction. The extent of contamination is bounded laterally by two clean monitoring points, but no well is available to provide a boundary to the plume in the direction of ground water flow. In Figure 2(a), contamination extends between two clean monitoring points for an unknown distance and may, therefore, impact a down-gradient dwelling. This scenario may occur even if the clean wells are closer together, as shown in Figure 2(b). In Figure 2(c), an additional monitoring location has been installed and determined to be clean, which eliminates the illustrated building from consideration for additional PVI investigation assuming that there are no preferential transport pathways present that could lead to PVI. This example illustrates that ground water flow directions and monitoring well locations should be carefully considered when defining the lateral inclusion zone. Section 2.3.2.2 provides a methodology to account for ground water flow direction and locating monitoring wells.

Extending the inclusion zone by a distance equal to the distance between monitoring wells is an arbitrary choice. This ratio is recommended as a starting point. If a caseworker has local knowledge that justifies either a greater or lesser ratio, that local knowledge should be applied and the ratio adjusted accordingly. The ratio should be based on local regulatory policy and the distribution of existing and potential receptors around the release site.

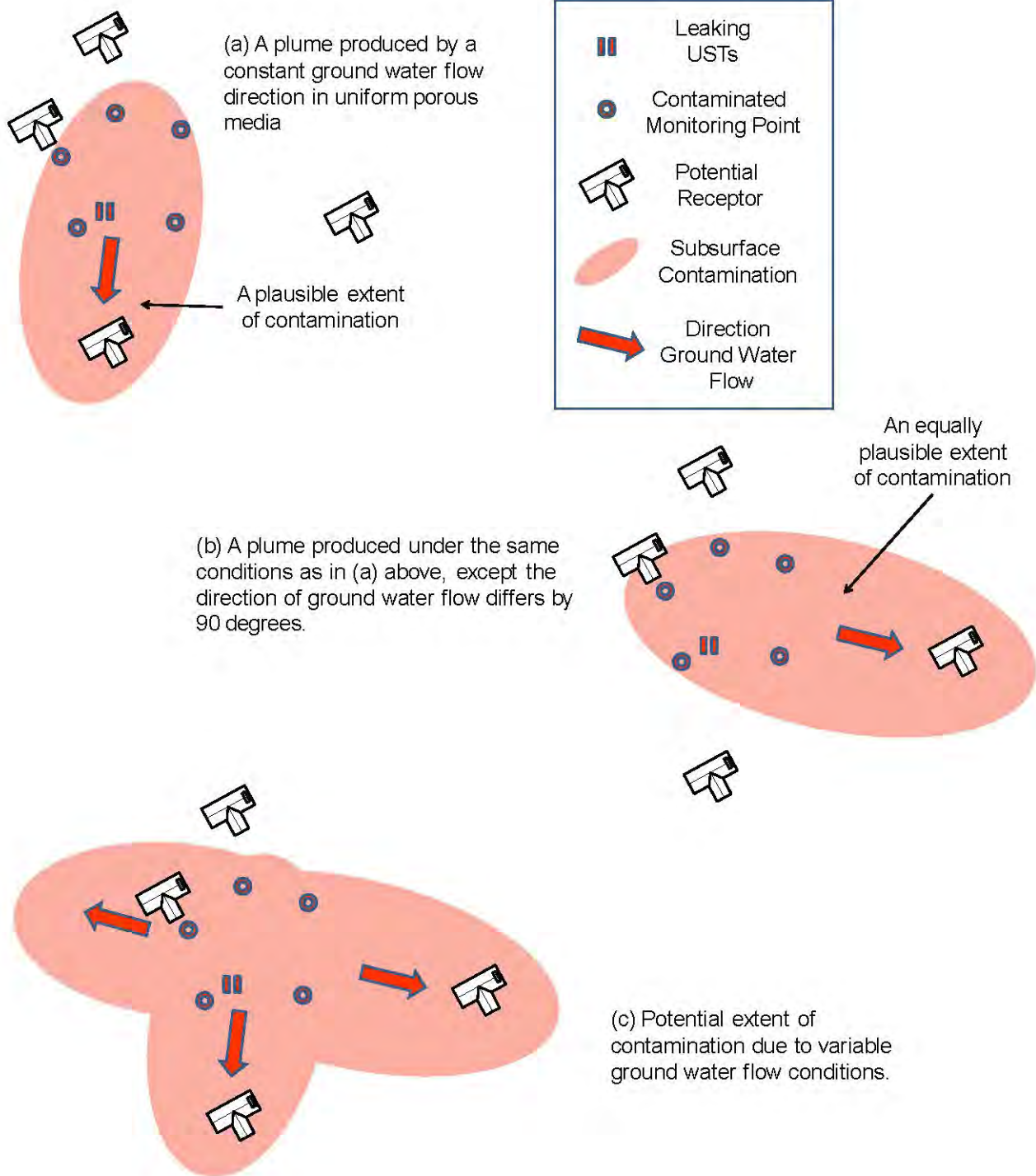


Figure 1. *Examples of Plausible Extent of Contamination for Hypothetical Petroleum Release*

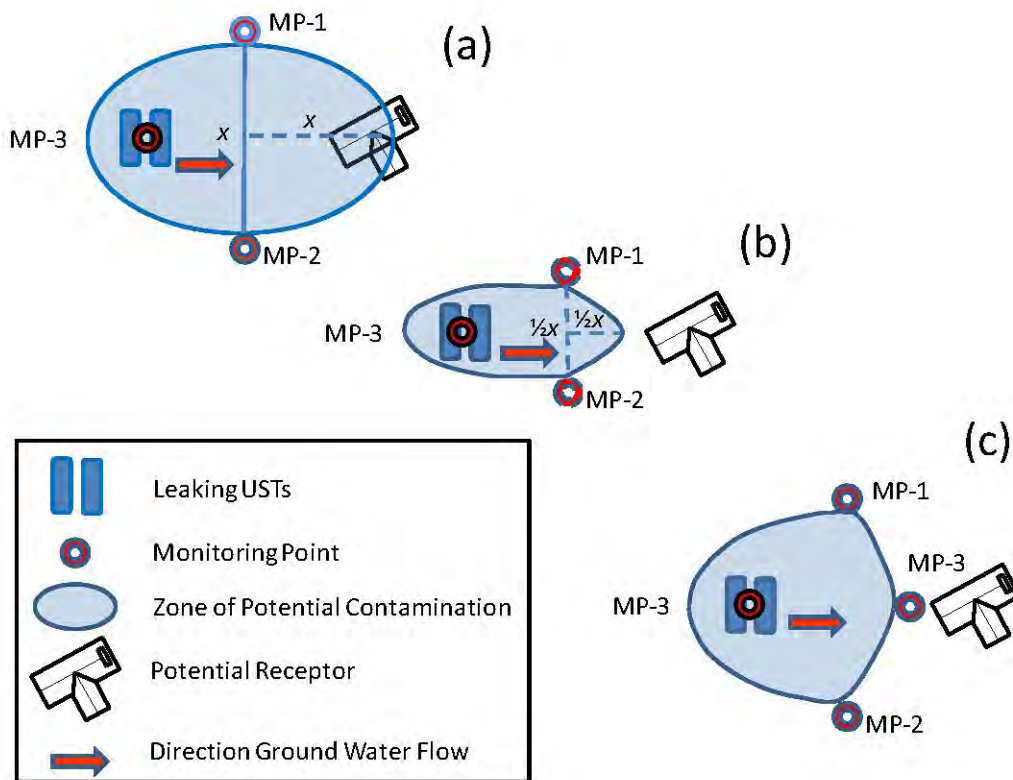


Figure 2. Effect of the distance between clean monitoring points on the extent of the plausible zone of potential contamination.

The ratio of one-to-one in the judgment of the authors is a good point of departure for unconsolidated media. In fractured consolidated media, particularly if the hydraulic gradient is aligned with fracture orientation, a larger ratio would be appropriate.

Strictly speaking, no matter how close together they are, the contaminant concentration between two monitoring points is never known with absolute certainty; it can only be extrapolated. Because there is a practical limit to the number of monitoring points that can be installed, there will always be some degree of uncertainty. The techniques described in this Issue Paper recognize the uncertainty inherent in the site investigation process and represent one approach for balancing between being overly protective and not sufficiently protective. Site-specific data regarding the actual extent of

contamination and its potential for migration are necessary for defining the lateral inclusion zones.

2.1 Process to Define the Lateral Inclusion Zone

Figure 3 illustrates the process of defining the inclusion zone. In this example, a first round of sampling showed that the UST resulted in contamination of all five wells surrounding the leaking UST (red circles, e.g., representing borehole locations). New monitoring locations were installed to establish the extent of contamination (blue circles). Soil samples and ground water samples from the new location were found to be clean. In this case, the maximum extent of contamination may be presumed to be defined by the smoothed shape bounding the clean monitoring points (Figure 3(a)). EPA recommends that dwellings (e.g., House A) within the area of presumed maximum extent of contamination are to be evaluated for

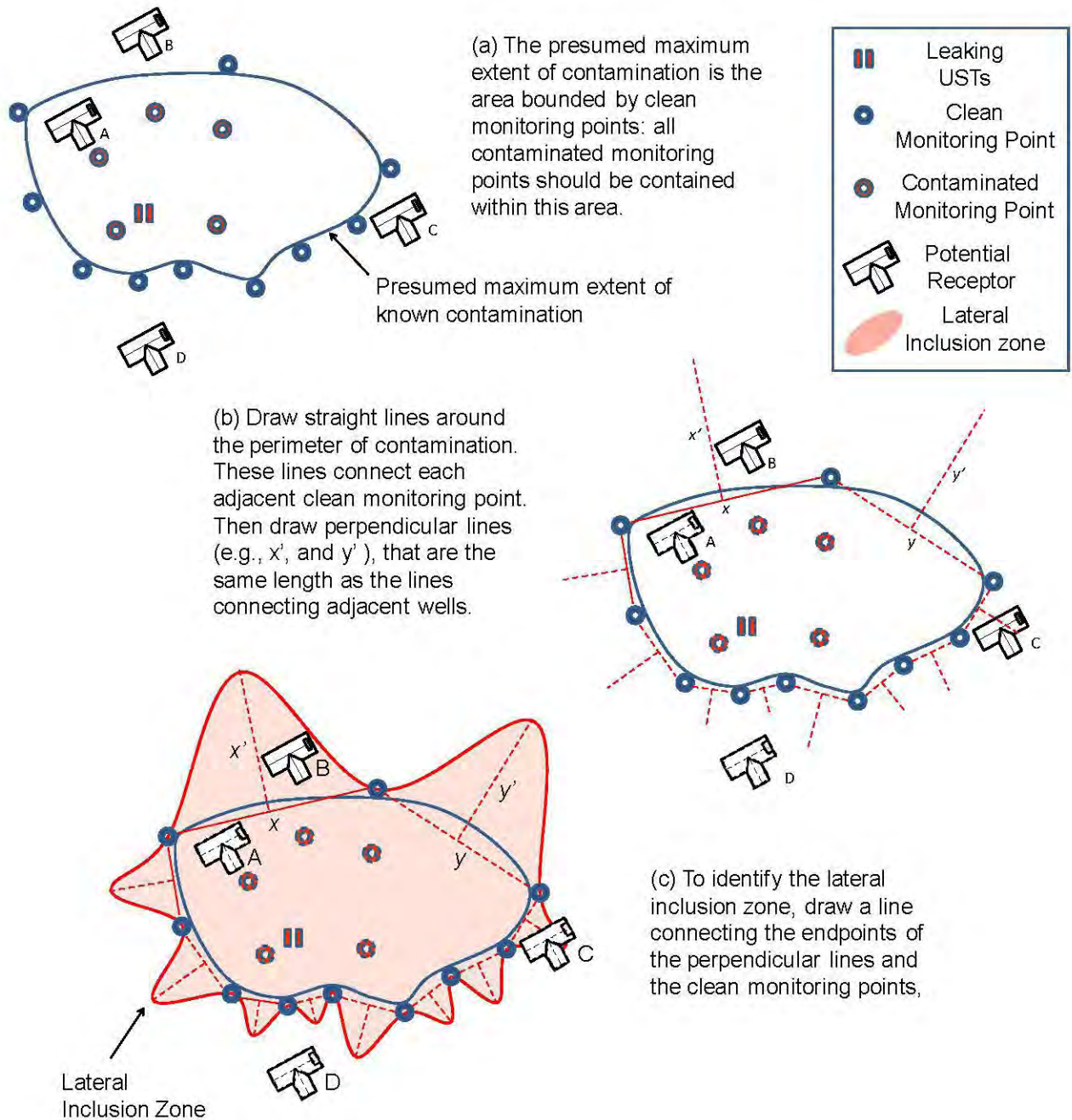


Figure 3. *Determination of lateral inclusion distance based on separation distance between clean monitoring points*

potential PVI impacts. While Houses B, C, and D are outside the presumed maximum extent of contamination, there is uncertainty about the extent of contamination between monitoring locations, particularly where monitoring points are separated by a large distance.

The uncertainty in the presumed maximum extent of contamination may be accounted for by extending the inclusion zone beyond the presumed maximum extent of contamination (defined by the blue line in Figure 3(a)). This concept is illustrated in Figures 3(b) and 3(c). Any building within the inclusion zone defined in this manner is recommended for further evaluation. If any portion of a structure falls within the inclusion zone, all of the structure is considered to be within the inclusion zone. With this concept of inclusion zone, Houses B and C, in addition to House A, are recommended to be investigated for potential vapor intrusion impacts.

This example illustrates that more closely spaced monitoring locations allow for greater certainty in defining the areas likely to be impacted by vapor intrusion and, generally, will reduce the areal extent of the inclusion zone. This example also illustrates that it is important to carefully consider the placement of monitoring points relative to receptors, so that portions of a building are not unnecessarily included in the inclusion zone.

The lateral inclusion zone is defined by bounding the plume with clean monitoring points. However, defining the boundary of the plume is less important in those parts of the site with no occupied buildings. To minimize expense, monitoring points should be located so they provide the most usable information for both the initial site characterization effort and any follow-up assessment of vapor intrusion. Be sure to place monitoring points between the source of contamination and any potentially impacted buildings. This approach is followed in the example presented below in Section 2.3. In the example, a new well is placed in front of buildings that might be down gradient of the source, but where the edge of the plume is not well defined. In contrast, no additional work is suggested in areas that were upgradient of the source, or that did not have structures that would be vulnerable to PVI. For a new case the selection of the initial monitoring locations should be related to the locations of

buildings. These locations can be chosen to minimize the number of monitoring points installed.

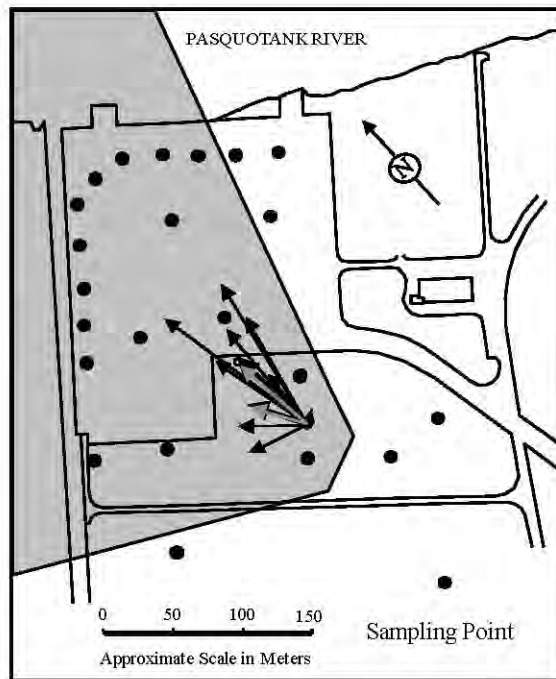
2.2 Dissolved Contaminant Plumes in the Lateral Inclusion Zone

Contaminant plumes are dynamic features and generally necessitate three-dimensional monitoring to assess the transient behavior of ground water flow and the transport of contaminants. In unconsolidated deposits, the contaminant plume should extend down gradient in the direction of ground water flow. However, a variety of hydrological phenomena can change the direction of ground water flow, including aquifer recharge following rainfall or snow melt, changes in the pumping of ground water, and tides or changes in the stage of a nearby river. Heterogeneity of geologic materials comprising the upper-most water bearing zone also may influence the direction of migration and extent of contaminant plumes. Plume behavior in heterogeneous materials may be quite different from that anticipated for homogeneous materials. In some cases plumes may be either narrower or broader, or bifurcated with lobes moving in different directions.

Changes in the direction of ground water flow are common at leaking UST sites (see Goode and Konikow, 1990; Mace et al., 1997; Wilson, 2003; Wilson et al. 2005a; Wilson et al., 2005b). Figure 4 illustrates variability of ground water flow directions at two leaking UST sites. In Figure 4(a), the flow direction as indicated by the cluster of arrows varies by more than 90 degrees. The fluctuation of ground water flow directions in Figure 4(b) ranges over nearly 180 degrees. Determination of flow direction may require periodic sampling over more than one annual cycle to understand the ground water flow regime at a given site. As the plume migrates, appropriate adjustments to the sampling plan should be made to ensure that potential receptors continue to be protected.

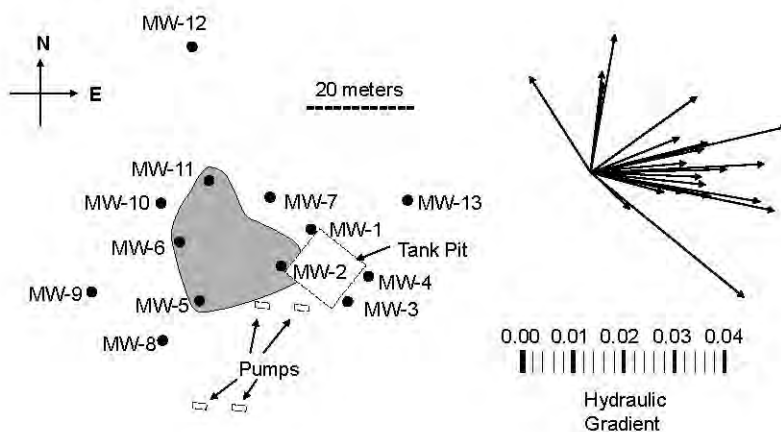
EPA recommends that ground water elevations be measured when the wells are sampled so that the direction of ground water flow can be determined for that particular sample round.

A



(a) An MTBE site in Elizabeth City, NC. The arrows represent the distance that water would move in one year, based on the direction and hydraulic gradient present in a particular round of sampling. The origin of the arrows is the center of the LNAPL source area. The black dots are locations of monitoring wells. The shaded area includes all the monitoring wells with concentrations of MTBE above 20 $\mu\text{g/l}$. Reprinted from Figure 3.1. of Wilson et al. (2005a).

B



(b) A leaking UST site in New Jersey. The arrows represent the distance that water would move in one year, based on the direction and hydraulic gradient present in a particular round of sampling. The origin of the arrows is the center of the LNAPL source area (shaded gray). (Wilson et al., 2005b)

Figure 4. Relationship between the distribution of contamination in ground water and the variation in direction and magnitude of ground water flow

2.3 Steps to Apply a Lateral Inclusion Zone

There are four general steps in defining a lateral inclusion zone:

1. Map and estimate the extent of contamination at the site with existing monitoring points.
2. Define an inclusion zone. Consider ground water flow direction.
3. Determine if additional monitoring points could be used to reduce the extent of the inclusion zone.
4. If information is available, test the inclusion zone against simple transport calculations, and adjust the inclusion zone as required.

Srinivasan et al. (2004) used a site in South Carolina as a case study to illustrate the implementation of a software application that can be used to identify the optimum locations of monitoring wells. The Optimal Well Locator (OWL) is further described in Section 2.3.2.2.1. This Issue Paper will use the same site as a case study to define a lateral inclusion zone for ground water contamination.

The data used in the case study are provided as an illustration. They do not necessarily reflect current conditions at the site, and have no bearing on past or current regulatory action taken by the South Carolina Department of Health and Environmental Control.

2.3.1 Map and Estimate the Extent of Contamination

The first step is to obtain a map showing the distribution of contamination and the location of potential receptors at the site. Figure 5 in this paper is a reproduction of Figure 5 originally presented by Srinivasan et al. (2004). The source of contamination is located in a commercial area extending along an arterial highway. On the other side of the contaminated area are four residential houses. The contours on the map showing the general distribution of contamination do not include the houses that may potentially be impacted by PVI; however, there are no clean wells between the source of contamination and these potential receptors.

Close examination of the contours shows that the boundaries of the plume, even if based on an

interpolation scheme, are arbitrary; the location of the 10 µg/L, 100 µg/L and 1,000 µg/L contours are unsupported by data over most of their length. There are no wells that bound the lateral extent of contamination between the 10 µg/L contour and the houses. The location of the toe of the plume (i.e., the longitudinal extent of the plume) beneath Circus Donuts is similarly unsupported by data by any wells that define the longitudinal extent of the plume. The contours present a highly subjective depiction of the extent of contamination, limiting it to the commercial area without justification based on the data. As a result, the available data for this site does not support understanding of potential impacts to the neighboring houses.

2.3.2 Define an Inclusion Zone

It is not necessary for the first definition of the inclusion zone to consider the direction of ground water flow. At recent petroleum release sites, this information may not be available. The most conservative assumption is that contamination can move in any direction, and that movement in any particular direction is equally plausible. This approach to define the inclusion zone is described in Section 2.3.2.1.

If data are available that can be used to infer the direction and magnitude of ground water flow, then information on ground water flow can be used to refine the Inclusion Zone. Approaches to accomplish this are described in Section 2.3.2.2. In addition, it may be necessary to install additional monitoring wells to adequately define the lateral exclusion zone. Approaches for selecting appropriate well locations are described in Section 2.3.3.

2.3.2.1 A Definition That Does Not Consider Ground water Flow

The general approach was illustrated schematically in Figure 3. Clean monitoring locations are used to establish a boundary around the presumed maximum extent of contamination. Then segments are drawn that extend the lateral inclusion zone past the presumed maximum extent of contamination. The extension of the inclusion zone compensates for the uncertainty in the true limit of contamination in the space between the monitoring points. The approach is applied to the case study beginning

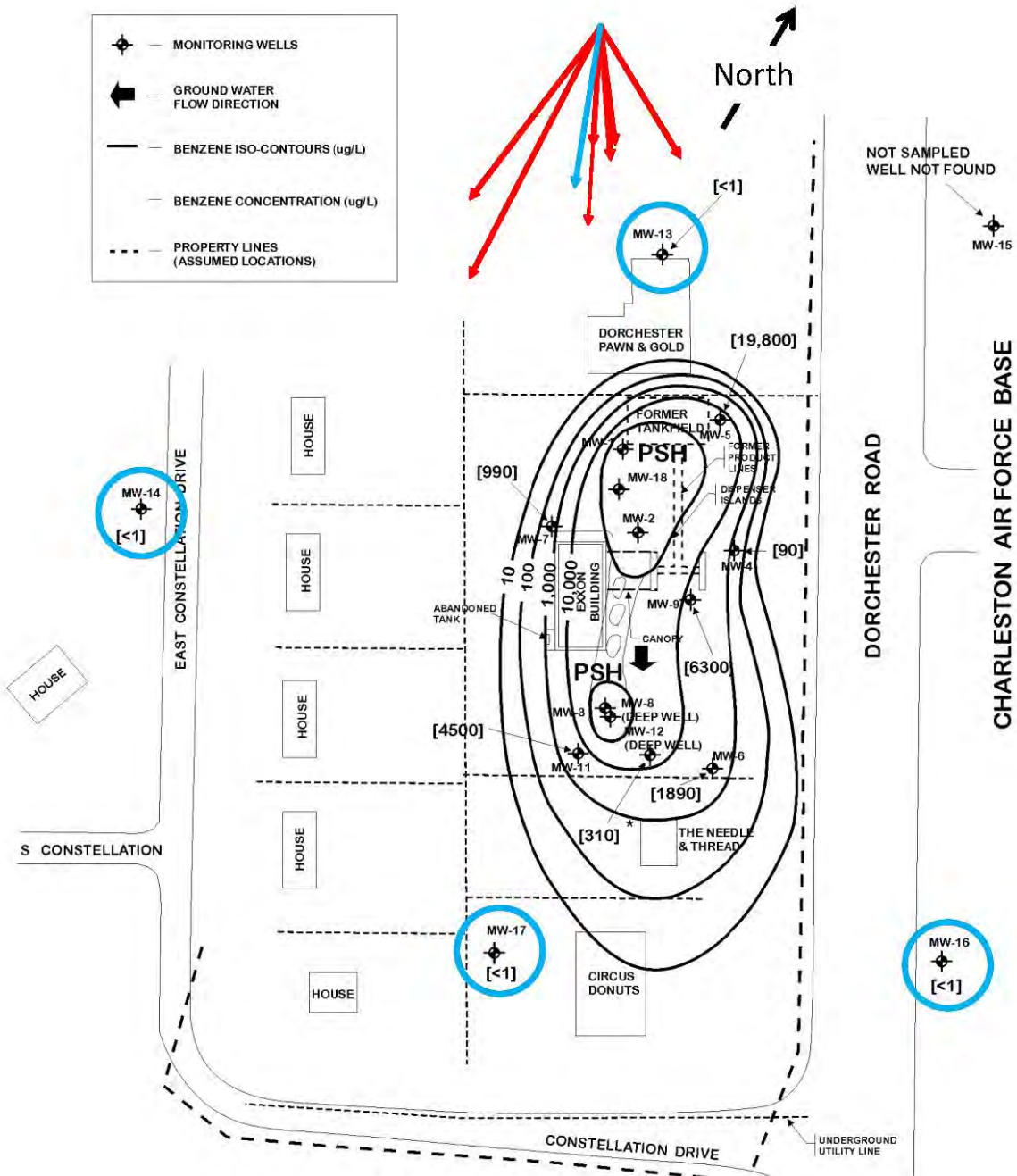


Figure 5. Distribution of benzene in ground water at a UST release in South Carolina. The red arrows are the distance that ground water would be expected to move in three years based on the hydraulic conductivity and porosity of the aquifer and the hydraulic gradient that pertained in a particular round of sampling. The heavy blue arrow is the distance water would move under average conditions in five years. Circled wells have concentrations of benzene less than the detection limit.

with Figure 6, which shows segments connecting clean monitoring points to establish the maximum presumed extent of contamination.

The figures in this Issue Paper were created using an accompanying EXCEL spreadsheet titled ***Inclusion Zone Calculations***. The spreadsheet can facilitate the calculations necessary to apply the approach to other sites. The spreadsheet contains two tabs that facilitate finding the angle between well pairs. Use the following process to define an inclusion zone on a map of a site. Using M.S. Word, PowerPoint or some similar computer application, “insert” a straight line over the line between two monitoring wells on the map of the site. Then cut the line and paste it onto the chart in the tab ***Angle Comparison***. Select the line segment and move it around on the chart until the axis of rotation of the line segment passes through the point (0,0). Then open the tab ***Data Angle Comparison***, and change

the value for the direction of a test angle (Cell D21) by trial and error until the line in ***Angle Comparison*** labelled “test angle” converges with the line pasted into ***Angle Comparison***. The value of the angle where the lines converge is the direction of the line segment.

Evaluation continues for well pairs moving clockwise around the perimeter as defined by the clean wells. See Table 1 and Figure 7. The direction of the line segment between wells in Table 1 is presented in Degrees from North with the first well named in the line segment as the axis of rotation. A clockwise rotation is a positive direction and a counter clockwise rotation is a negative direction. The direction of the new line segment associated with each well pair is simply 90° less than the direction of the segment between wells. The resulting lateral inclusion zone is depicted in Figure 8.

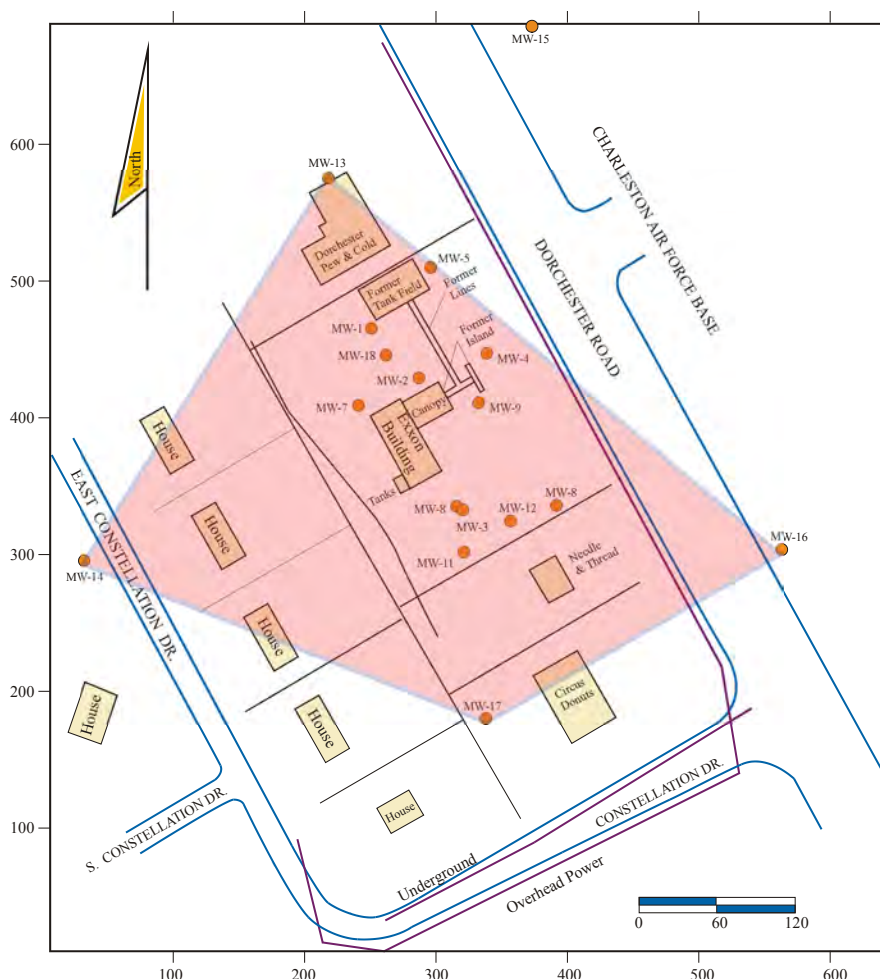


Figure 6. Area enclosed by the perimeter of clean monitoring wells (shaded red).

Table 1. Calculations to correct the length of a new line segment for the probability that ground water will flow in that direction. See Figure 6 for the line segments.

Line between Wells	Direction Line Segment between Wells	Direction of New Line Segment	Distance between Clean Wells	Weight on New Line Segment	Ratio New Line Segment to Distance Between Wells	Length of New Line Segment
	Degrees right of North	Degrees right of North	Feet			Feet
MW-13 to MW-16	129	39	444	0.0000	1	0
MW-16 to MW-17	240	150	260	0.9451	1	246
MW-17 to MW-14	291	201	328	0.1408	1	46
MW-14 to MW-13	33	-57	344	0.0000	1	0

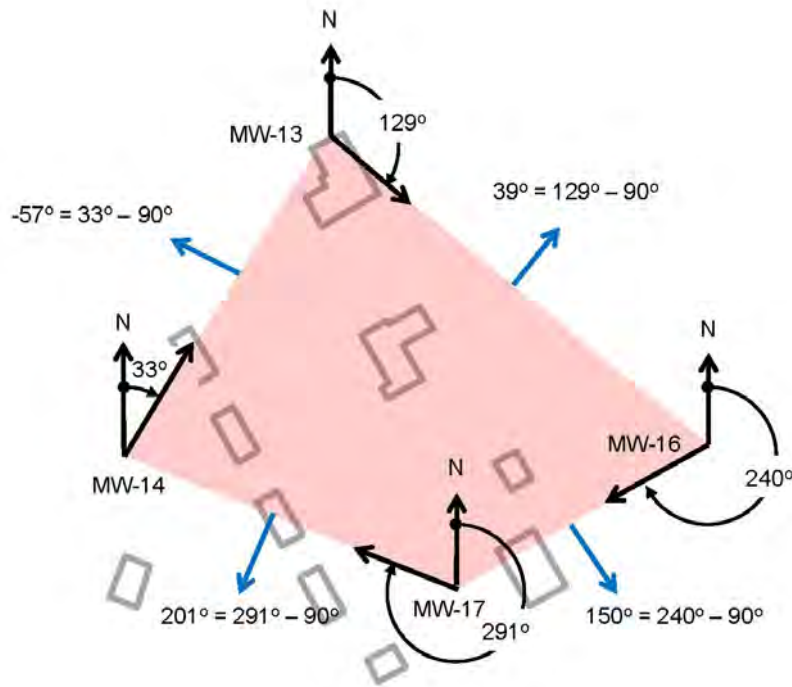


Figure 7. The area enclosed by the perimeter of clean monitoring wells (shaded red) with angles of line segments that connect the monitoring wells measured clockwise from North. For the line from MW-14 to MW-13, the angle is 33° past a complete circle. Extensions of the inclusion zone are directed 90° from the lines connecting the monitoring wells. For example, between MW-13 and MW-16 the outward extension is 129° – 90° = 39°, and between MW-14 and MW-13 the outward extension is 33° – 90° = - 57°.

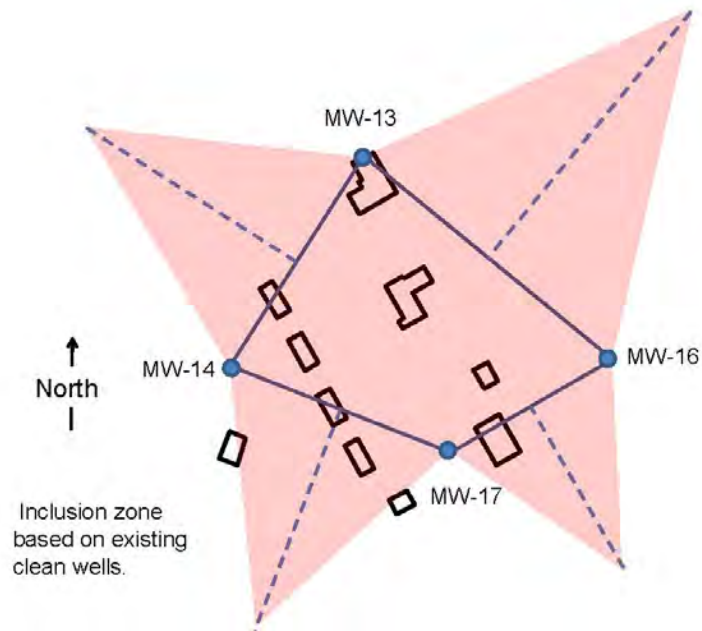


Figure 8. Lateral inclusion zone defined without using information on ground water flow directions.

2.3.2.2 A Definition that Considers Ground water Flow

At sites where the flow field is primarily unidirectional and the aquifer can be said to be homogeneous and isotropic, contaminant plumes tend to be elongated in the down gradient (longitudinal) direction and extend to a smaller degree in the lateral (transverse) direction. If historical ground water monitoring data are sufficient to provide a high degree of confidence in defining the extent of the plume, then it may be reasonable to reduce the extent of the inclusion zone in the lateral direction in proportion to the ratio of the longitudinal to the transverse extension of the plume. To make the comparisons between lateral and transverse extension of a plume, it is best to have data describing the seasonal variability in flow direction and velocity, and data from wet years and dry years. Note: this information is not typically available at the beginning of an investigation of a leaking UST. Therefore, more conservative criteria are generally used, which results in a larger lateral inclusion zone to compensate for the uncertainty and variability in the ground water flow direction.

Panel (a) of Figure 9 depicts a situation in which the plume is roughly circular, with extension in the

longitudinal direction (x) equal to extension in the transverse direction (y). Though a circular plume is not common, this situation may be encountered when the ground water flow field is highly variable throughout the year or when a ground water mound forms beneath a tank excavation. In such a case, the inclusion zone could extend outward from clean monitoring points to the same distance as the spacing between the monitoring points. Note that the inclusion zone may also extend some distance in a direction that may later (after sufficient data have been collected) be considered to be upgradient from the source.

Panel (b) of Figure 9 depicts a plume which extends twice as far in the longitudinal direction as it does in the transverse direction (or, to state this differently, the plume only extends half as far in the transverse direction as it does in the longitudinal direction). In this situation, the lateral inclusion zone could reasonably be extended in the transverse direction half the distance of the spacing between monitoring points along the sides of the plume. In the longitudinal direction, the inclusion zone would extend outward the same distance as the spacing between clean monitoring points. Panel (c) of Figure 9 is similar to Panel (b) except that the

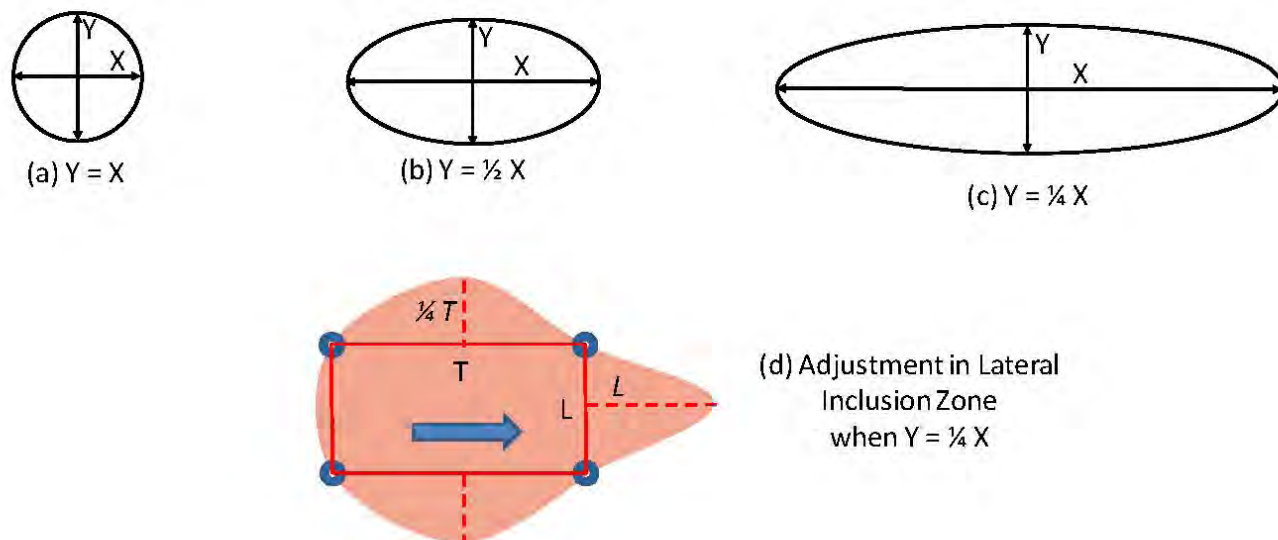


Figure 9. *Adjusting the Lateral Inclusion Zone to compensate for variations in flow directions.*

longitudinal extension is four times greater than extension in the transverse direction.

Panel (d) of Figure 9 applies this concept to define an inclusion zone for flow in one predominant direction, where the longitudinal extension is four times greater than extension in the transverse direction. The inclusion zone in the transverse direction would extend outward only one-quarter of the distance between the clean monitoring locations. These adjustments to the lateral inclusion zone can be made for a real site if additional ground water monitoring data are available on the changes in the hydraulic gradient and the flow direction for several rounds of sampling.

The transverse extension of a plume is generally presumed to be a consequence of transverse dispersion in flowing ground water. Because transverse dispersion coefficients are low (Gelhar et al., 1992), as a practical matter, the transverse extension of a plume more likely results from variations in ground water flow direction over time (Wilson et al., 2005a). Mace et al. (1997) collected data on the variation in flow direction at 132 gasoline stations in Texas. The median of the standard deviation of the direction of ground water

flow was 36 degrees. This extent in variation in the direction of ground water flow can easily account for the transverse extension of most plumes. At a site in North Carolina, Wilson et al. (2005a) used the elevation of water in wells to calculate the direction of ground water flow for thirteen separate monitoring events. The space occupied by the plume of contaminated ground water was the same as the space swept out by the variation in ground water flow direction (see Figure 4(a)).

2.3.2.2.1 Find the Average Direction of Ground water Flow.

The U.S. EPA provides a software application that can be used to estimate ground water flow directions. It was originally intended to guide the placement of additional monitoring wells at a site (Srinivasan et al., 2004). The Optimal Well Locator (OWL) uses linear regression to fit a plane to the elevation of ground water in wells during a particular round of sampling. The slope of the plane provides the best estimate of the overall hydraulic gradient and direction of ground water flow during that round of sampling. The OWL software is available at no cost on an EPA web site (see <http://www.epa.gov/ada/csmos/models/owl.html>).

The OWL computer application (Srinivasan et al., 2004) was used to analyze data on water elevations and fit a slope to the water table in each of seven rounds of sampling. Data were available on the hydraulic conductivity of ground water at the site, and a value for the aquifer porosity was estimated (Srinivasan et al., 2004). This information was used to estimate how far and which direction ground water would move under the conditions observed during each particular round of samples.

An EXCEL file titled **Inclusion Zone Calculations** is supplied with this issue paper. The vectors are presented in the tab **Flow Vectors**. The file contains the additional calculations used for the case study. The file can be used as a template to apply the calculations to another site. Data entry is in the tab **data Flow Vectors**.

The seven vectors estimate the distance that ground water would move at the site if it moved for three years following the hydraulic gradient in each of the seven rounds of sampling. The seven flow vectors are presented in red (see Figure 5); the average is represented by the blue vector. In general, ground water flow was not toward the residential houses, but some of the vectors indicated that there might be a concern that contamination might reach some of the houses. Notice that the flow vectors vary in both direction and length. Simply taking the mean and standard deviation of the flow directions would give equal

weight to short vectors and long vectors. If we assume that the variation in flow direction at the site is random, we can use the normal frequency distribution to estimate the fraction of the time that flow might be in a particular direction. To do that, we need to scale the variation in flow direction to the probability distribution. As an approximation, the flow direction was weighted by the lengths of the vectors.

The magnitude of the hydraulic gradient at the site varied from 0.01184 on 12/12/1995 to 0.02818 on 1/11/1999 (Table 2). Calculations of the Weighting Multiplier for each sampling period are presented under tab **Weight Multiplier** in the Excel file **Inclusion Zone Calculations**. The gradient in each sampling period was divided by the smallest gradient, and then the quotient was multiplied by ten to calculate the Weighting Multiplier (expressed to the nearest whole number). Results are presented in Table 2.

The weighting is accomplished in the tab **Weight Calculator** in the Excel file **Inclusion Zone Calculations**. The flow direction for each particular round of samples was entered multiple times into a column of data. The number of times a direction was entered was proportionate to the magnitude of the hydraulic gradient on that date. The number of times a flow direction is entered becomes the weight assigned to the data from that particular sampling date. The mean of all of the multiple entries of flow direction is an estimate of the average direction of flow, and the standard deviation

Table 2. Hydraulic gradients and flow directions were extracted for each round of sampling using OWL (red arrows in Figure 4). For each round of sampling the hydraulic gradient was used to select a weighting multiplier to be used to calculate an average flow direction and the standard deviation of the flow direction. The weighting multipliers are the number of times a direction was entered in tab **Weight Calculator** of the EXCEL file **Inclusion Zone Calculations**.

Date	Gradient	Gradient/Smallest Gradient	Weighting Multiplier (number of times to enter value in spreadsheet)
1/25/1994	0.0153	1.29	13
12/12/1995	0.01184	1.00	10
10/30/1998	0.01335	1.13	11
12/4/1998	0.01186	1.00	10
12/21/1998	0.02156	1.82	18
1/11/1999	0.02818	2.38	24
3/29/1999	0.0198	1.67	17

of all of the multiple entries of flow direction is an estimate of the variability in the direction of flow. The proportionality factor is arbitrary. However, to make the calculated mean and standard deviation a reasonable approximation of the “true” mean and standard deviation, the smallest hydraulic gradient should be entered at least ten times.

If many values are available for the magnitude and direction of ground water flow, entering the weighted values of flow direction into the **Weight Calculator** tab can be tedious. The tab **Weight Calculator (2)** automates the process to some extent. Enter data on the magnitude of ground water flow starting with cell A33 and data on the direction of flow in cell B33. Sort the entered data from the smallest value of magnitude of flow to the largest value for magnitude of flow. Click on cell C33, and select the box at lower right with the mouse, then pull down to extend the formula in row C across all the cells. Multiply the ratio of the gradient to the weakest gradient by ten, and then enter the nearest whole number that corresponds to the ratio in the corresponding cells starting with D33.

The spreadsheet uses nested IF statements to populate the weighted flow directions (X) in column G. The spreadsheet then calculates the square of the weighted flow directions (X²) in column H. Copy the numbers that are greater than zero from cells in column G and H, select *paste special*, and paste them into cells in columns I and J as *values*. Excel 7.0 only allows seven nested IF statements. If there are data available from more than seven dates, insert the data from the first seven dates, copy and paste the data from columns G and H into columns I and J. Then erase the data in columns G and H and insert the data from the second seven dates. Copy and paste the numbers from columns G and H into columns I and J, inserting the new numbers below the previous numbers. Continue the process until columns I and J contain the weighted flow directions (X) and the square of the weighted flow directions (X²) that correspond to all available values for the magnitude and direction of ground water flow.

The angles extracted using OWL were then entered into tab **Weight Calculator** in the Excel file **Inclusion Zone Calculations**. The flow direction on 12/12/1995 was entered 10 times and the

flow direction on 1/11/1999 was entered 24 times (weighting multiplier in Table 2). Similar entries were made for the other dates. By following this procedure all the multiple entries for all of the dates were used to calculate an overall mean and standard deviation. For this data set, the overall flow direction was 157 degrees clockwise from North, with a standard deviation of 22 degrees (cells H11 and H12 of tab **Weight Calculator**). To find the weight for a particular direction, enter the direction in cell H7. The weight relative to the average direction of ground water flow appears in cell H9.

2.3.2.2.2 Assign a Weight to the Extent of the Inclusion Zone for the Direction of Ground Water Flow

The probability that ground water will flow in a particular direction is taken as the solution to the probability density function $\phi(z)$.

$$\phi(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}$$

The value of a particular direction of flow is entered in cell H7 of tab **Weight Calculator**. The spreadsheet calculates a z score for that particular direction by subtracting the particular direction from the mean direction, then dividing the difference by the standard deviation. The z score is reported in cell H15. For the value of z, the spreadsheet calculates a value of the probability density function, $\phi(z)$, and then divides by the value of the probability density function that applies when all the flow is in the average direction of flow and $z=0$. This value is reported in cell H9 of tab **Weight Calculator**. This value will be used as a weight to correct the default distance for expansion of the inclusion zone for the probability that ground water will flow in the direction entered in cell H7 of tab **Weight Calculator**. The length of the perpendicular bisector constructed for each line segment is equal to the product of the weighting factor and the distance separating the wells at the ends of the line segments.

Examine Figures 7 and 8. The direction of the line segment between MWV-13 and MWV-16 is 129 degrees clockwise from North. The expansion of the inclusion zone is along a line perpendicular to the segment between MW-13 and MW-16. The direction of that line is $129^\circ - 90^\circ = 39^\circ$. When 39

is entered into cell C1 of the calculator in the tab **Weight Calculator** it returns a weight of 0.0000. The probability that water will move upgradient across the line segment between well MW-13 and MW-16 is so small that it can be ignored (weighting factor less than 0.01). Weighting factors for these line segments are presented in the fifth column of Table 1. The weighting factor for the line segment between MW-13 and MW-14 is also 0.0000, thus for both of these segments, it is not necessary to extend the inclusion zone. For the segments between MW-16 and MW-17 and between MW-17 and MW-14, the inclusion zone extends outward, but in both of these cases the distance is less than that separating the monitoring wells. Figure 10 shows the reduced inclusion zone.

Tab **New Line Segment** of the **Inclusion Zone Calculations** spreadsheet uses the distance between the clean monitoring wells and the ratio between the length of the new line segment and the distance between the clean wells to calculate the length of the new line segment.

2.3.3 Determine if Additional Monitoring Points Would Reduce the Extent of the Refined Inclusion Zone

With the information on the direction and length of the new line segments between well pairs, draw a new perimeter that connects the clean wells and the ends of the line segments that are projected from the mid-points between clean well (see Figure 10). Compare Figure 8 and Figure 10. Although the inclusion zone is much reduced, the four houses that are immediately to the West of the contaminated area are still in the inclusion zone. There may be benefit in installing additional monitoring points.

In Figure 11, a hypothetical new well is located approximately half way between the region with known contamination and the houses under consideration. If the well is clean, for the cost of one monitoring well, the inclusion zone can be redefined and no longer includes the four houses under consideration. Selecting the best location for a new well involves a trade-off. If the new well is located too close to existing contaminated

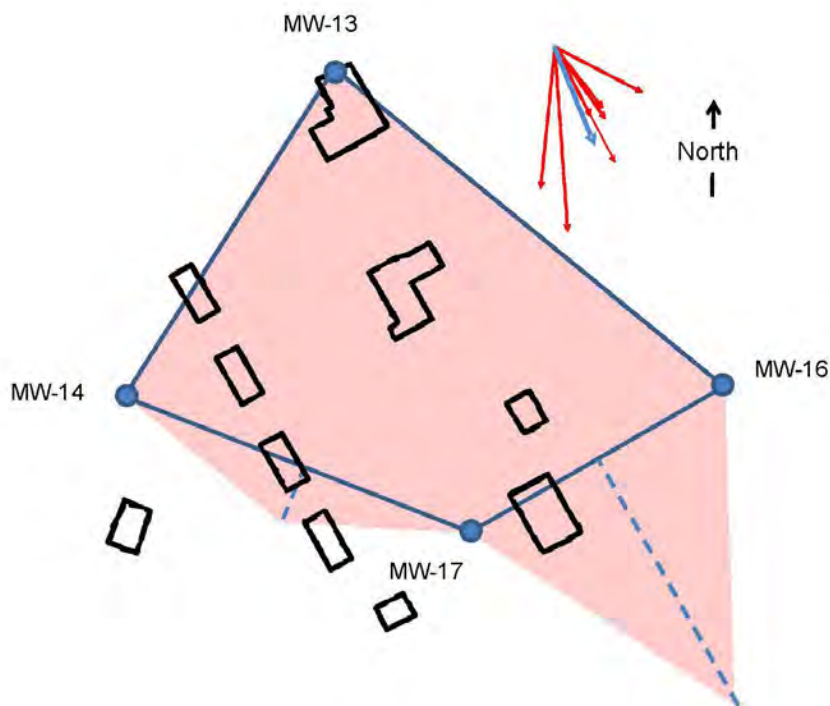


Figure 10. A Lateral Inclusion Zone defined using information on ground water flow

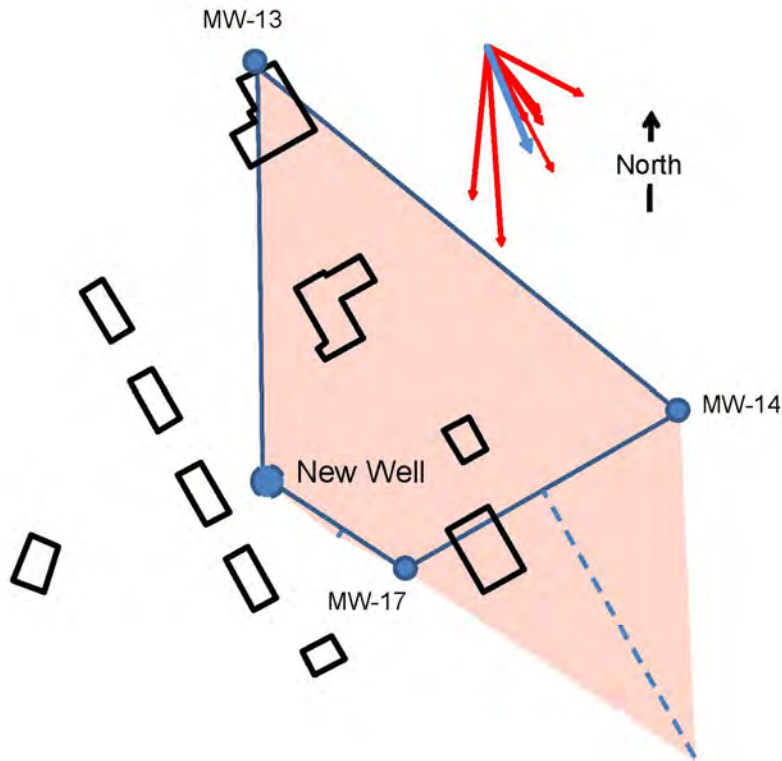


Figure 11. One possible outcome of the evaluation after a new well is installed to better define the Lateral Inclusion Zone.

wells, there is a good chance that it will also be contaminated and will not help to refine the inclusion zone. If a new well is located too close to a structure (e.g., directly adjacent to the structure of concern), it is possible that some portion of the footprint of the structure will be in the lateral inclusion zone, even if the well is clean.

After assessing the need for additional wells, install those that are needed and sample and analyze ground water to redefine the space assigned to the inclusion zone. If a structure is contained within a lateral inclusion zone, then the structure should be evaluated to determine if it is within the vertical inclusion zone as described in Section 3.0

The above discussion presumed that the initial site characterization was conducted without consideration of a lateral inclusion zone (or petroleum vapor intrusion). Thus the lateral inclusion zone extent is being added to the existing site conceptual model. If the definition of the lateral inclusion zone is planned initially as a part of the site assessment, then some effort may be minimized. For example, monitoring wells could be

located initially to assess building impacts, as was done with the additional well placed in Figure 11.

2.3.4 Test the Inclusion Zone Against Simple Transport Calculations

The contaminant transport equation provides a means to forecast the distance that a contaminant might travel with flowing ground water. Because choices must be made for parameters whose true values are unknown or uncertain, the forecasts from the transport equation are rough estimates rather than definitive guides. However, the rough estimates provide a second line of evidence that can be used to evaluate the inclusion zones. Equations for a one-dimensional, steady-state transport equation solution are given in Appendix C. U.S. EPA provides a calculator to forecast plume length with these equations at <http://www.epa.gov/athens/learn2model/part-two/onsite/length.html>. The calculations are also provided under tab **Plume Lengths** in the EXCEL file **Inclusion Zone Calculations**.

For three of the monitoring wells in the case study, an estimate of hydraulic conductivity (K_s)

was available from rising head slug tests in the wells. Values were input into Column C of *Plume Lengths*. The initial concentration of benzene along the flow path was assumed to be the concentration in the well. Values were input in Column K. The final concentration along the flow path was taken to be 0.14 mg/L. This is the target ground water concentration corresponding to the target indoor air concentration when the indoor air attenuation factor is 0.001 (U.S. EPA, 2002). This value was input into Column L. The average hydraulic gradient was 0.0174 (Cell D11 in tab *data Flow Vectors*). This value was input into Column E of tab *Plume Lengths*.

The target ground water concentration is derived from a target indoor air concentration for benzene of 31 $\mu\text{g}/\text{m}^3$ (U.S. EPA, 2002 Table 2a). The air concentration was divided by the dimensionless Henry's Law constant (0.22 = mg/L in air divided by mg/L in water) to get an equivalent concentration in water, and then multiplied by 1000 to allow for attenuation of concentrations between benzene in soil gas beneath a building and concentrations within the building.

Ground water contaminated with petroleum hydrocarbons is consistently anaerobic. Suarez and Rifai (1999) reported that the mean rate constant for anaerobic biodegradation of benzene at 45 field studies was 0.003 per day, corresponding to a half life of 230 days. Falta et al. (2012) recommends a first order rate constant of 1.1 per year (equivalent to a half life of 230 days) to model anaerobic degradation of benzene at gasoline release sites. Data from a variety of field and laboratory studies are collated in the tab *Rates of Benzene Degradation* in the EXCEL file *Inclusion Zone Calculations*. Most of the rates were published in Aronson and Howard (1997). The median half life was 248 days.

A half life of 230 days was used to make the first estimate of plume length, and as a sensitivity analysis, a half life of 693 days was also used to estimate plume length. A value for the degradation half life of 693 days includes 75% of the half lives collated under tab *Rates of Benzene Degradation*.

Values for half life are input in Column G of tab *Plume Lengths*. A sensitivity analysis was also performed with reasonable values of the effective porosity. Values of 0.20 and 0.25 were input into Column D of tab *Plume Lengths*.

In Column O of tab *Plume Lengths*, the spreadsheet calculates the lengths of the plumes that are forecast for these specified conditions. The calculations use a value for the longitudinal dispersivity (α) that is input in Column I of tab *Plume Lengths*. The spreadsheet uses the formula of Xu and Eckstein (1995) to estimate an appropriate value of α from the calculated length. Manually input different values for α into cells in Column I until the input value in Column I matches the calculated value in Column J. When values in Columns I and J agree within a foot, the value for the plume length in Column O can be taken as the forecast of plume length.

Table 3 provides the plume lengths from the sensitivity analysis. As a worked example, the forecast of plume length for the plume originating from MW-11 was calculated as follows. Where the hydraulic gradient (H) is 0.0174 foot per foot, the hydraulic conductivity (K_s) is 1.66 feet per day, and the effective porosity (θ) is 0.25 ft^3 per ft^3 ; the seepage velocity (v) is:

$$v = \frac{H * K_s}{\theta} = \frac{0.0176 * 1.66}{0.25} = 0.1156 \text{ feet per day}$$

Where the half life of natural biodegradation is 230 days, the first order rate constant (λ) is 0.003013 per day. For well MW-11, the initial concentration of benzene (c_0) is 4.5 mg/L (see Figure 4). As mentioned above, the acceptable concentration of benzene (c) is taken to be 0.14 mg/L. Input of trial values for the longitudinal dispersivity (α) into Column I of tab *Plume Lengths* predicts a value of α of 10 feet, based on the plume length equation from Appendix C.

$$x = \frac{2\alpha \ln \frac{c}{c_0}}{1 - \sqrt{1 + \frac{4\lambda\alpha}{v}}} = \frac{2 * 12 * \ln \left(\frac{0.14}{4.5} \right)}{1 - \sqrt{1 + \frac{4 * 0.003013 * 10}{0.1156}}} = 162 \text{ feet}$$

Figure 12 plots the plume lengths in Table 3 against two configurations of the inclusion zone. The

Table 3. Maximum plume length forecast from the maximum concentration of benzene in a monitoring well, the hydraulic conductivity at that location, and an estimate of effective porosity and degradation half life.

Concentration (mg/L)	Hydraulic Conductivity (feet per day)	Effective Porosity (ft ³ /ft ³)	Half Life (days)	Maximum One-dimensional Plume Length (feet)
MW-9				
6.3	0.77	0.20	230	106
6.3	0.77	0.20	693	300
6.3	0.77	0.25	230	88
6.3	0.77	0.25	693	242
MW-11				
4.5	1.66	0.20	230	198
4.5	1.66	0.20	693	560
4.5	1.66	0.25	230	162
4.5	1.66	0.25	693	453
MW-6				
1.89	2.21	0.20	230	191
1.89	2.21	0.20	693	546
1.89	2.21	0.25	230	153
1.89	2.21	0.25	693	440

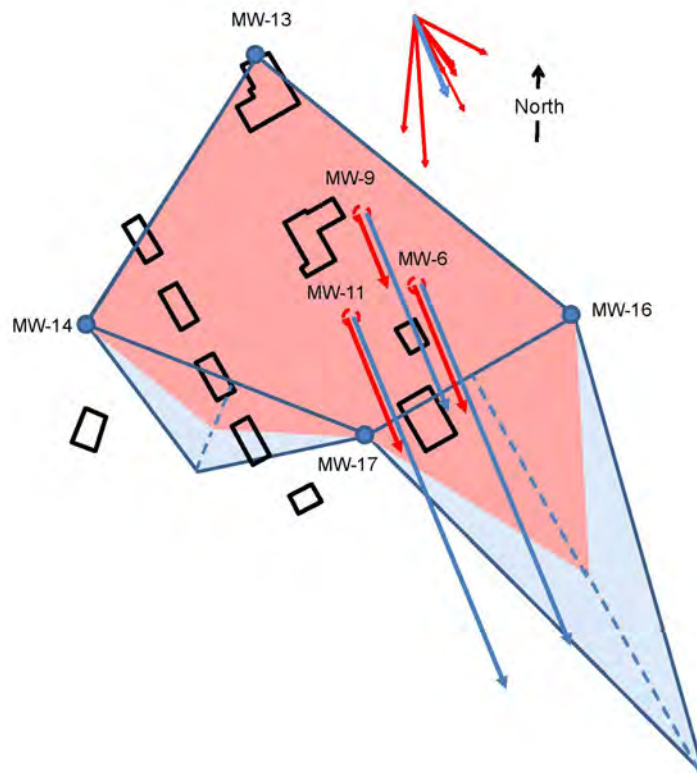


Figure 12. Comparison of forecasts of plume lengths to two configurations of the inclusion zone.

red arrows originating at wells MW-9, MW-6 and MW-11 in Figure 12 correspond to the forecasts associated with a porosity of 0.25 and a half life of 230 days. The blue arrows correspond to a half life of 693 days. The arrows extend in the average direction of ground water flow.

In the red-colored inclusion zone, the ratio of the distance that the inclusion zone extends past the clean wells to the distance between the clean wells is set at 1.0. The lengths of the plumes that are predicted from the average rate of benzene biodegradation in ground water (red arrows) are contained within the red inclusion zone. For average conditions, there is no evidence from the forecast that the inclusion zone is not protective.

However, this is not the case for plume lengths that are based on a rate of degradation that would include 75% of rates in the literature (the blue arrows). The forecast plume lengths from wells MW-6 and MW-11 extend past the red inclusion zone. To make the inclusion zone conform to the forecast for well MW-6, it was necessary to set the ratio at 2.0 (blue-colored inclusion zone. It is not possible to adjust the inclusion zone to include the forecast from well MW-11 with any reasonable ratio of distances.

This process should be repeated for every well within the area enclosed by clean monitoring wells using well-specific input parameters. The forecasts have the most value to understand the expected locations of the plume where no monitoring data are available (such as the forecast from well MW-6). The forecasts have less value for regions that are represented by real monitoring data (such as the forecast from well MW-11 compared to the measurement at well MW-17).

Although the inclusion zone seems to be greatly expanded by the forecast, it must be recalled that there are no monitoring data to support the assumed location of the toe of the plume (Figure 5). Adding a monitoring well in the primary direction of ground water flow would greatly increase the credibility of the site assessment, and very likely reduce the size of the inclusion zone.

If information is available about the flow of ground water at the site, this information can be used to adjust the configuration of the inclusion zone. If information about the flow of ground water is not

available, then the configuration of the inclusion zone must be determined by professional judgment or by local policy. Over time as information is collected on actual impacts to residences and the impact that was predicted by a particular configuration of the inclusion zone, it will be possible to optimize this screening process.

3.0 THE VERTICAL INCLUSION ZONE

After characterizing the extent of contamination and defining a lateral inclusion zone, there still may be a number of residences potentially at risk for vapor intrusion. At this point, the vertical separation criteria should be applied. Table 4 provides example vertical separation-distances based on Davis (2009) and Cal EPA (2012). The separation distance for ground water contamination is the distance between the lowest part of the structure of concern and the highest historical elevation of the water table. The separation distance for LNAPL is the minimum extent of clean soil that is required between the contaminated sample and the receptor. It is not the separation distance between the contaminated sample and the receptor. There may be additional contamination in soil between the sample and the receptor. In addition, data on the stratigraphy at the site, which should be incorporated into the CSM, should be considered in determining whether there is sufficient oxygen in the subsurface to promote aerobic biodegradation or whether relatively impermeable layers may prevent the intrusion of vapors into overlying buildings.

The limits on the vertical separation distance that would cause a structure to be included in a vertical inclusion zone are based on experience with biodegradation of vapors of petroleum hydrocarbons in the unsaturated zone (Lahvis et al., 1999; API, 2000; DeVaul, 2007; Davis, 2009; Cal EPA, 2012). There are two important assumptions in applying the vertical separation distance: that the soil is “clean” and that there is adequate moisture in the soil to support biodegradation of the hydrocarbon vapors.

For a PVI investigation, “clean” soil does not necessarily mean that it is contaminant-free, but rather that the level of any contamination present is low enough so that the biological activity of the soil is not diminished and the subsurface environment will support sufficient populations of microorganisms

Table 4. Example conditions for a structure to be included in the Vertical Inclusion Zone. If any condition applies, the structure is in the Vertical Inclusion Zone.

These conditions are provisional and are for illustration purposes only. They are based on Davis (2009) and Cal EPA (2012). At such time as U.S. EPA Office of Underground Storage Tanks (OUST) issues the *Guidance for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites*, the conditions for vertical separation in the Guidance will supersede the conditions in this table.

Media	Benzene Concentration	TPH Concentration	Vertical Separation Distance* (feet)
Soil (mg/kg)	≤10	≤250	<6
	>10 (LNAPL)	>250 (LNAPL)	<15
Groundwater (µg/L)	≤5,000	≤30,000	<6
	>5,000 (LNAPL)	>30,000 (LNAPL)	<15

The thresholds for LNAPL indicated in this table are indirect evidence of the presence of LNAPL. These thresholds may vary depending on site-specific conditions (e.g., soil type, LNAPL source). Investigators may have different experiences with LNAPL indicators and may use them as appropriate. Direct indicators of LNAPL also apply; these include measurable accumulations of free product, oily sheens, and saturated bulk soil samples. For more information, see API (2000).

* The vertical separation distance represents the thickness of clean (TPH ≤ 250 mg/kg), biologically active soil between the source of PHC vapors (LNAPL, residual LNAPL, or dissolved PHCs) and the lowest (deepest) point of a receptor (building foundation, basement, or slab). EPA recommends that sub-slab sampling be conducted to evaluate the risk of PVI whenever contamination above the specified threshold is present in any sample and the distance between the contamination and an overlying building is less than these vertical distances.

to aerobically biodegrade PHC vapors. As a point of departure, soil with less than 250 mg/kg TPH can be considered “clean.” State agencies may choose a different definition based on their local conditions and circumstances. The California Environmental Protection Agency uses a value of 100 mg/kg (Cal EPA, 2012).

Establishing that there is adequate moisture to support growth of bacteria is a substantial challenge in desert climates. U.S. EPA (2013a) notes that soil moisture content greater than 2% is adequate to support biodegradation activity (Leeson and Hinchee, 1996). However, biodegradation is limited when the moisture content is at or below the permanent wilting point (Zwick et al., 1995; Holden, Halverson, and Firestone, 1997). Adequate soil moisture is indicated if the landscape supports the growth of indigenous vegetation (Riser-Roberts, 1992). Agencies in states with desert landscapes may wish to take advantage of their local knowledge and apply local criteria.

3.1 Steps to Apply a Vertical Separation Distance to Core Samples

There are five steps to defining a vertical inclusion distance:

1. Acquire core samples or a series of core samples that represent the entire interval from the receptor to the lowest potential location of the water table.
2. Screen the core samples in the field with an Organic Vapor Meter (OVM) to determine if samples should be acquired for laboratory analysis. If contamination is detected by the OVM screening, analyze the sediment samples for the concentrations of Total Petroleum Hydrocarbons and for Benzene.
3. Compare depths and concentrations of contaminants in core samples to the Vertical Separation Distance Criteria.
4. Acquire a sample of ground water and analyze for concentrations of TPH and Benzene.

5. Compare depths to ground water and concentrations of contaminants in ground water to the Vertical Separation Distance Criteria.

3.1.1 Acquire Core Samples for Screening

Determining the vertical separation distance for contamination in the unsaturated zone can be challenging. To apply the criteria in Table 4, it is necessary to document that the clean soil is in fact clean. Exterior bulk soil samples should be collected from near the perimeter of the building in the direction of the source of contamination. To avoid missing a depth interval that might be contaminated, it is necessary to recover a complete profile of core

samples from the land surface to the water table. If possible, it is better to recover core samples to a depth equal to the lowest elevation of the water table over time.

To assure that the core profile is complete, compare the length of the core that is recovered (including material in the core retainer and the cutting shoe) to the depth interval that the core barrel was driven into the earth. In some subsurface materials, core samplers driven two or three feet will recover an equivalent length of core sample, but core samplers driven four or five feet will not. Adjust the depth interval driven in each core if necessary to recover a complete core sample.

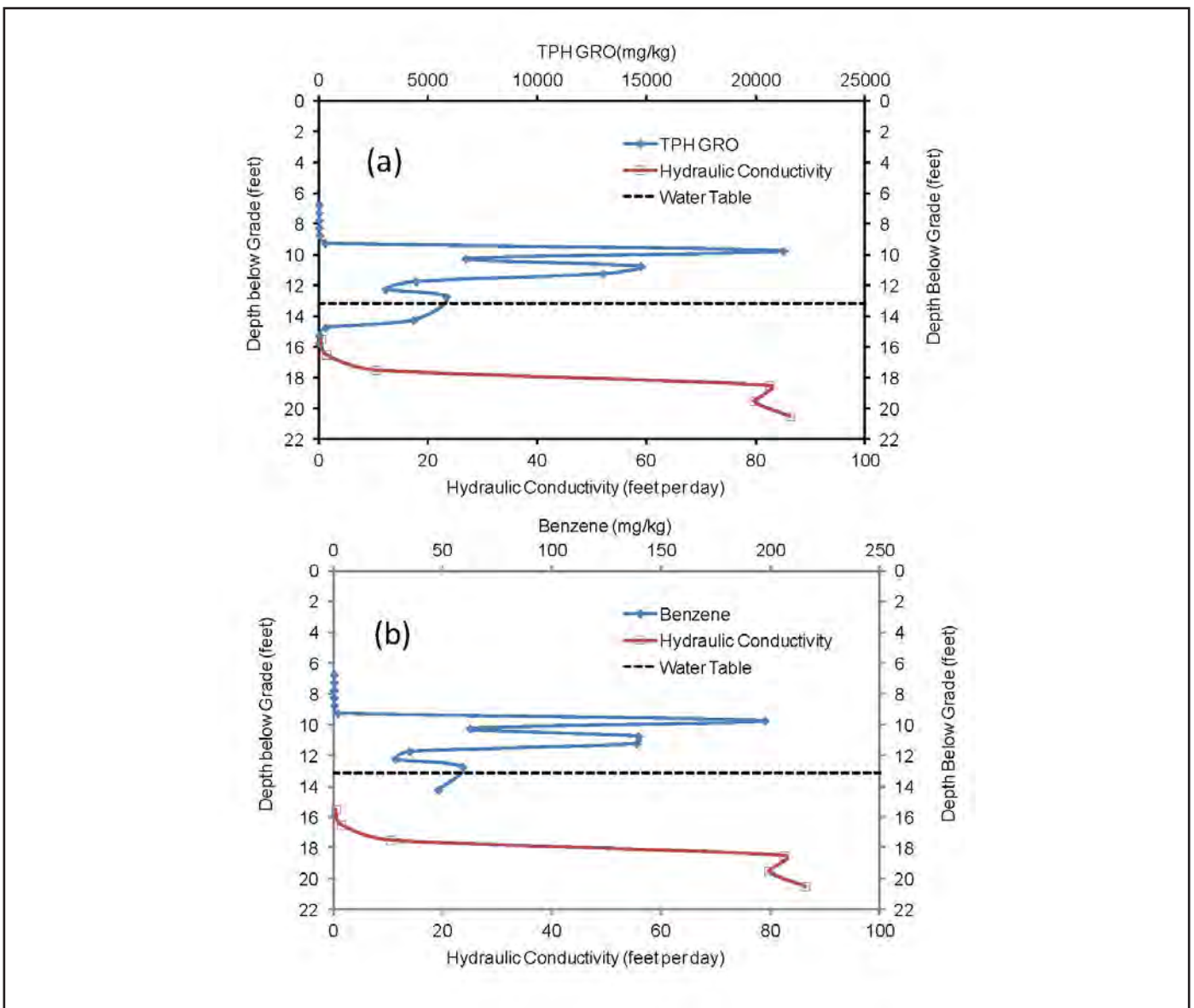


Figure 13. Distribution of TPH (panel a) and benzene (panel b) and hydraulic conductivity with depth below land surface at a gasoline release site in Golden, OK.

On occasion, material with a high concentration of TPH will literally be well lubricated, and will fall out of the core sampler as it is being recovered. Do not ignore the missing sample. Attempt to collect core samples in an adjacent bore hole, starting just above the elevation that would correspond to the missing sample, and drive the core sampler the maximum interval that will acquire a complete core sample.

Figure 13 compares the vertical distribution of Total Petroleum Hydrocarbons (TPH) at a site in Oklahoma. Point estimates of hydraulic conductivity at the site were made with a pneumatic slug test (Butler et al., 2002). Notice at the site that the greater mass of TPH was confined to material that has low hydraulic conductivity. Petroleum hydrocarbons tend to be held by capillary attraction to fine textured materials. At many gasoline service station sites, the first aquifer to produce enough water to allow sampling by a monitoring well is effectively a confined aquifer. Much of the time, the free water surface will be up in the fine textured material containing the TPH, and much of the TPH will be covered in water and not in contact with soil gas. In times of drought, the free water surface often will drop to the contact between the fine textured material containing the TPH and the transmissive material that comprises the aquifer proper. During times of drought, more of the TPH in the fine textured material may be in contact with soil gas.

If a nearby monitoring well is available, determine the depth to the free water surface. If an established monitoring well is not available, determine the depth to water in the borehole used to acquire the core samples. Examine the texture of the core samples taken in the depth interval across the free water surface. If the material has a fine texture, and particularly if the borehole stays open, continue to acquire core samples until more transmissive material is reached.

Apply the Soil Media Criteria in Table 4 to the TPH values, even if the material is below the water table at the time the cores were acquired.

3.1.2 Screen Core Samples for Subsequent Laboratory Analysis

In the past, core samples for analysis of TPH were often acquired at an arbitrary depth below grade

or an arbitrary depth above the location of the water table at the time of sampling. This sort of conventional sampling is illustrated in Figure 14. At the site in South Carolina, the depth from land surface to the water table varied from six to eight feet. Over this vertical interval up to five samples were taken for organic vapor monitoring.

The OUST guidance applies criteria based on the thickness of clean, biologically active soil between the top of the contamination and the receptor (U.S. EPA. 2013a). To apply the criteria, it is necessary to document that the soil is clean across the entire separation distance between the contamination and the receptor. To minimize the chance of missing a contaminated depth interval, it is good practice to screen the core samples with an Organic Vapor Monitor (OVM) every 0.5 foot starting at 1.0 foot below land surface or 1.0 foot below the bottom of the structure of concern. Continue screening until the depth of the core samples exceeds the lowest possible position of the water table. If the OVM meter reading exceeds 100 ppm, a sample should be analyzed in the laboratory for benzene and total petroleum hydrocarbons (TPH). Detailed recommendations for extracting and analyzing core samples are provided in Appendix A.

Figure 13 presents the vertical profile of TPH resulting from a gasoline release in Golden, Oklahoma. The concentration of TPH in the interval from 7 feet to 9 feet below grade was ≤ 29 mg/Kg. Notice the sharp increase in concentrations of TPH and benzene in core material at a depth that is just less than 10 feet below land surface. The concentration of TPH at a depth of 9.75 feet was 21,000 mg/kg and the concentration of benzene was 197 mg/Kg.

3.1.3 Compare the Distribution of Contamination in Sediment to the Vertical Separation Criteria

A recent study by EPA (2013b) indicates that for an oxygen shadow to form beneath a building, and thus appreciably reduce the effectiveness of biodegradation to prevent PVI, three conditions must be met: the building must be very large (including the surrounding impermeable cover), the source of vapors must be highly concentrated, and the vapor source must be in relatively close proximity to the bottom of the building. For a

typical single family dwelling, it will generally be sufficient to collect exterior soil vapor and bulk soil samples from only one location immediately adjacent to the structure on the side facing the source of contamination. The screening criteria applied will be based on the sample analyses from this one location. For larger structures, it may be necessary to collect samples and apply the criteria at several locations along the building perimeter and potentially from locations on all sides of the building.

The criteria for the vertical separation distances are provided in Table 4. If either of these criteria for vertical separation is satisfied, this site is in the vertical inclusion zone, and requires further assessment. As indicated in Figure 13, the site in Oklahoma is in the vertical inclusion zone because there was less than 15 feet of clean soil between the receptor and the first bulk soil sample with >250 mg/L of TPH. The separation distance to the receptor was the land surface because the receptor had a pier-and-beam foundation.

3.2 Steps to Apply a Vertical Separation Distance to Ground Water Samples

Applying the vertical criteria for ground water is less challenging. Install a monitoring well in the borehole used to acquire the core samples, and sample ground water for analysis of benzene and TPH. Measure the elevation of the water table in the new well. If a nearby monitoring well has an extensive monitoring record, use the variation in water table elevations in the older well to estimate the variation in elevation of the water table at the new location. Compare the elevation of the bottom of the structure of concern to the highest elevation of ground water under the structure. The vertical separation for ground water does not make allowance for the capillary fringe. Compare the vertical separation to the free water surface.

At the site in South Carolina as depicted in Figure 14, the depth to water at the structure of concern is near 8 feet. If there is no residual TPH in the unsaturated zone, the inclusion zone is based solely on the depth to contaminated ground water. A depth of 8 feet is greater than a separation distance of 6 feet as described in Table 4. The structure of concern would not require any further investigation if the concentration of benzene in ground water is ≤ 5 $\mu\text{g/L}$ and TPH is ≤ 30 mg/L .

At the site in Oklahoma as depicted in Figure 13, the depth to the free-water surface was 13.2 feet. However, the aquifer did not yield significant water until a depth of 17 feet, which is considerably below the major mass of residual gasoline. The concentration of benzene in the ground water was 823 $\mu\text{g/L}$ and the concentration of TPH was 12,300 $\mu\text{g/L}$. Based on the concentration of benzene or TPH in ground water and the separation distance, this site would not be in the vertical inclusion zone, and would not require further action. However, as the site failed the soil screening (i.e., TPH at a depth of 9.75 feet was 21,000 mg/kg), additional investigation for PVI is recommended. This example illustrates the importance of acquiring bulk soil samples for analysis, and not relying on ground water samples alone.

The data used in the case study are provided as an illustration. They do not necessarily reflect current conditions at the site, and have no bearing on past or current regulatory action taken by the Oklahoma Corporation Commission.

4.0. NEXT STEPS

Approaches to screen for PVI are not limited to the approach presented in this Issue Paper. The inclusion zones discussed in this Issue Paper are defined by proximity to contaminated ground water or to LNAPL hydrocarbons in the unsaturated zone. If a structure is in the inclusion zone as defined by benzene or TPH in ground water or TPH in core samples, one possible next step is to evaluate the concentrations of hydrocarbons in the soil gas. Samples of soil gas can be acquired from sub-slab monitoring points, or vapor probes, and analyzed for contaminants of concern such as benzene. The measured concentrations can then be compared to concentration limits in the OSWER draft guidance for evaluating vapor intrusion (U.S. EPA 2002).

The possibility of vapor intrusion of petroleum hydrocarbons is inversely related to the possibility of aerobic biodegradation of the petroleum vapors in the unsaturated zone (DeVaul, 2007). In turn, the possibility of biodegradation is related to the separation distance, the oxygen demand of the all the hydrocarbons in soil gas at the source of the

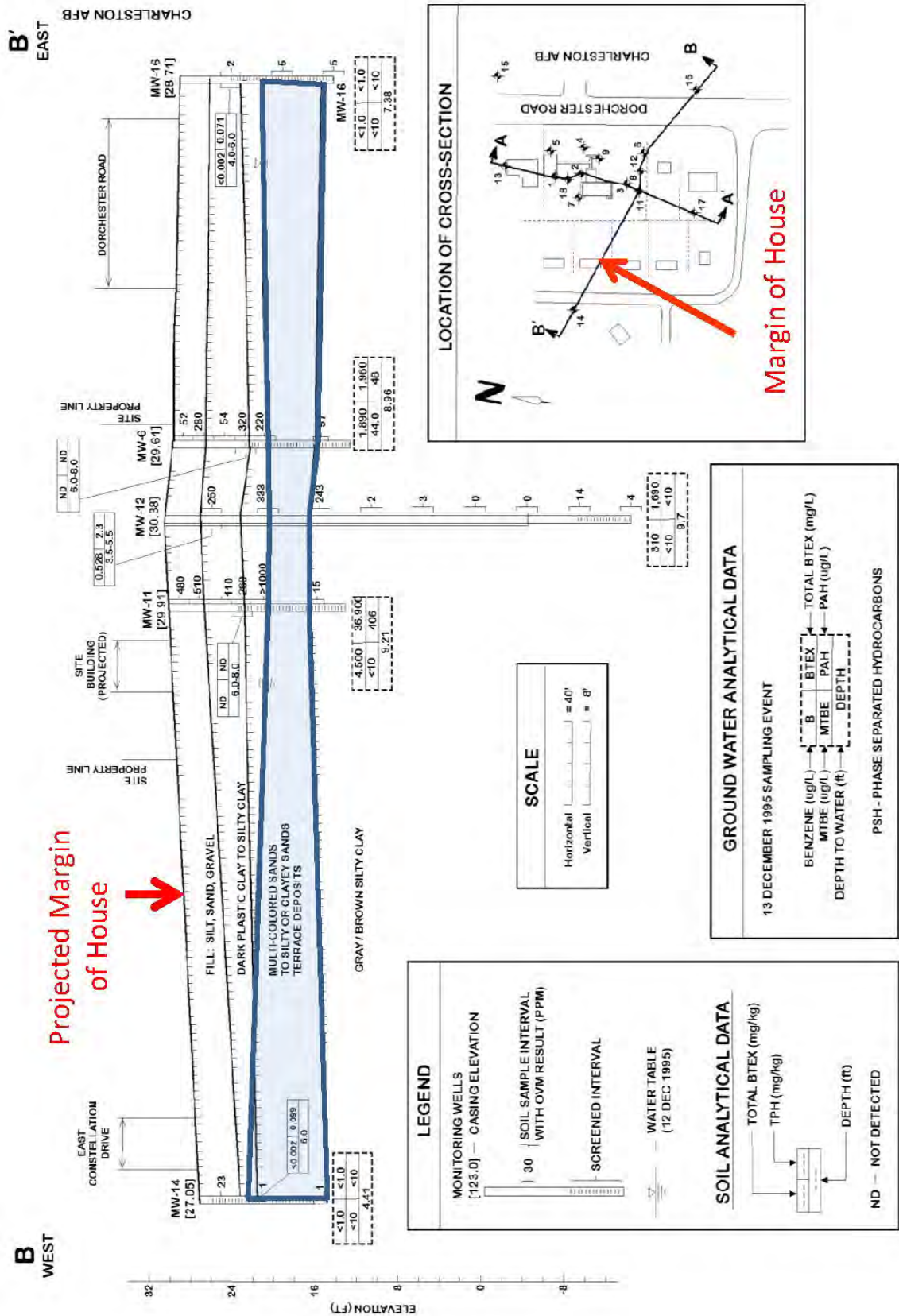


Figure 14. Projected depth to ground water at a structure under evaluation. Figure composed from Figures 2 and 3 in Srinivasan et al., (2004).

vapors, and the concentration of benzene at the source.

Another approach is to use these parameters to screen sites for PVI. The ratio of the concentration of benzene in indoor air to the concentration of benzene in vapors at the source is called the attenuation factor (U.S. EPA 2002). Abreu et al., (2009) performed computer simulations that predicted the effect of biodegradation on the attenuation factor. The results of a large number of complex simulations are summarized in a simple figure that plots the attenuation factor against the total oxygen demand for a variety of separation distances. In their approach, the figure is used to predict an attenuation factor that is specific for conditions at a particular site. To complete the evaluation, the attenuation factor is multiplied by the measured concentration of benzene in soil gas at the source of the vapors.

The approach of Abreu et al. (2009) may have application at many sites. However, it is important to attain a robust estimate of the total oxygen demand. Jewell and Wilson (2011) applied the approach to several gasoline release sites in Oklahoma. They took precautions to measure methane in the soil gas as well as concentrations of petroleum hydrocarbons. At three of eleven sites, including the contribution of methane to the total oxygen demand caused the predicted indoor air concentration of benzene to exceed the U.S. EPA Generic Screening Level for indoor air (9.8E-03 ppm v/v). The sites would not have exceeded the Generic Screening Level if the oxygen demand was calculated from the concentration of petroleum hydrocarbons alone.

Conventional ground water monitoring wells at gasoline service stations are usually screened across the water table. This means that monitoring wells can often be used to collect soil gas. Jewell and Wilson (2011) used conventional wells to acquire their soil gas samples. At many sites, it may be possible to use the same wells that were previously used to screen ground water to screen soil gas.

5.0 SUMMARY

U.S. EPA's *Guidance for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites* (U.S. EPA, 2013a) is intended to provide general criteria to identify structures that are at risk from petroleum vapor intrusion (PVI). This issue paper provides one approach to apply criteria set forth in U.S. EPA (2013a), but does not represent U.S. EPA guidance.

An inclusion zone is used to recognize structures that may be at risk from PVI. The inclusion zone generally consists of a lateral zone based on the delineation of a clean perimeter and a vertical zone based on the vertical separation distance between the structure and contamination in the subsurface.

The delineation of the lateral inclusion zone in this approach recognizes the fact that the lateral separation distance between a residence and contaminated ground water is dependent on the identification of the edge of a contaminant mass, whether it is mobile LNAPL, residual LNAPL, or a dissolved plume. Many sets of site characterization data do not explicitly define this boundary, but rely on drawn contours that may be arbitrary. In this approach, the lateral inclusion zone depends on the delineation of a clean perimeter. If monitoring points at a site are scarce or are widely separated, there will be uncertainty about the location of contamination in the areas between the monitoring points. A building may be at risk even though it is marginally outside the clean perimeter. The approach provides a reasonable procedure to extend the lateral inclusion zone based on the location and spacing of monitoring points. As site monitoring data are collected over time, the lateral inclusion zone may be reduced in its extent.

Once a lateral inclusion zone is identified, it can be further refined to optimize the screening process and avoid unnecessary risk characterization within buildings. As is shown in the examples in this Issue Paper, it may be necessary to acquire more data before the approach can be used with confidence to screen structures for PVI. The lateral inclusion zone may present a clear picture of the best locations for new wells. Ground water flow directions vary at most sites, so data collected over time on the direction of ground water flow can be used to refine the inclusion zone, very possibly shrinking

it. If information is available on the hydrological characteristics of the site, a simple transport and fate model can be used to forecast the lateral extent of contaminated ground water from particular wells. These forecasts can provide an additional line of evidence to evaluate or further refine the lateral inclusion zone.

After identifying a lateral inclusion zone, there still may be a large number of residences potentially at risk for vapor intrusion. At some sites it may not be possible to define a lateral inclusion zone. At this point, the vertical inclusion criteria should be applied. This Issue Paper recommends five simple steps to determination of the vertical extent of clean soil between the building and the contamination below the building, and to compare that extent of clean soil to the criteria for vertical separation distance in U.S. EPA (2013a).

In combination, definition of lateral and vertical inclusion zones make the best use of site characterization data for assessing the risk of PVI to structures at a LUST site. Ultimately, a useful prediction of the possibility of petroleum vapor intrusion in a particular building depends on knowledge of contaminant transport and transformation, and the site-specific distribution of contaminants. The procedures outlined in this Issue Paper provide a realistic data-driven approach to screen buildings for vulnerability to PVI.

NOTICE

The U.S. Environmental Protection Agency through its Office of Research and Development conducted the research described here as an in-house effort. This Report has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document.

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APPENDIX A. RECOMMENDATIONS FOR SAMPLING AND ANALYSIS

The conventional practice to sample for Total Petroleum Hydrocarbons in some states is to take a bulk sample of sediment into a sealed jar, return the jar to the laboratory on ice, and store the jar in a refrigerator until a subsample was taken to be extracted. This practice can result in considerable loss of VOCs and produce erroneous results. The authors recommend that sediment samples for analysis of TPH and Benzene should be preserved in methanol in the field as soon as possible after the core samples are acquired. In the absence of other guidance, the authors recommend the procedures and requirements as described in Minnesota Pollution Control Agency (2008).

The authors have had good results using the following procedure to extract core samples into methanol. Plug-samplers were constructed before going to the field by cutting the end from a 10-ml plastic syringe (Figure A-1 & Figure A-2). A sediment core was acquired in an acetate liner. The core was cut through with a saw at the depth interval to be sampled (Figure A-3). Then a plug-sampler was driven into the exposed face of the core sample. The syringe plunger was used to provide suction to pull the sample into syringe barrel as the barrel was forced into the face of the core sample (Figure A-4). Each plug contained approximately 10 ml of soil and extended approximately 2.5 inches into the core. After all the necessary plug samples for a particular depth interval were acquired (Figure A-5), the core was measured and cut again to present a fresh face at the next interval to be sampled.

The authors have found it to be convenient to take all the samples that might be needed at the same time. These include one plug sample for field screening with an OVM, duplicate plug samples into methanol for analysis of TPH and benzene and a sample taken into a clean empty vial for analysis of moisture content. The duplicate plug sample for TPH and benzene provides a contingency if a sample is lost, and provided a field duplicate if one is needed for quality assurance purposes. If the OVM screening did not reveal contamination, the other samples were not analyzed. The samples that were extracted into methanol were returned to the laboratory and discarded as hazardous waste.

The plug sample for field screening was sealed into a plastic bag containing air. At a later time the headspace of the bag was analyzed with an organic vapor meter (OVM) (Figure A-6). Our screening essentially followed Section A. Headspace Analysis of Minnesota Pollution Control Agency (2008).

Extraction vials were prepared by delivering 10 ml of purge-and-trap grade methanol into 40 mL Volatile Organic Analysis (VOA) vials. In the field, the plug samples were delivered into the vials (Figure A-7), the vials were sealed with the screw cap, and then the vials were shaken to begin the extraction and preserve the samples (Figure A-8). In the laboratory, the vials were shaken on a mechanical shaker for ten minutes. If this was not adequate to disperse and extract the plug, the vials were open and the plug was broken up with a spatula, and the vial was put back on the shaker for additional extraction. After the sediment was extracted, the vials were set out on the counter to allow the solids to settle. Then the vials were opened and the methanol extracts were taken for analysis. The methanol extract was diluted into distilled water, and the water was then analyzed by EPA Method 8260.

The final plug sample was used to determine the moisture content of the sediment sample. The plug was delivered into a clean empty 40 ml VOA vial. In the laboratory the sample was weighted, then dried to constant weight and weighed again.



Figure A-1. A sampler was constructed by cutting the end out of a plastic syringe.



Figure A-2. Commercial samplers are also available.



Figure A-3. A core sample acquired in a plastic sleeve is cut to access the core for sub sampling.

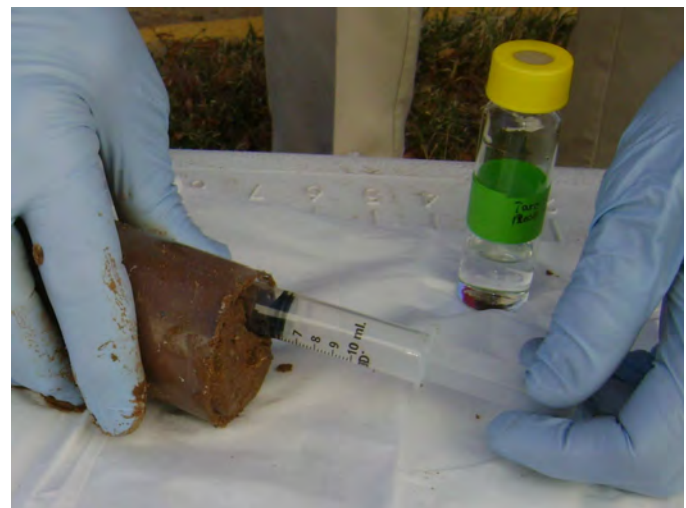


Figure A-4. A sampler is inserted into the cut face of the core sample to acquire a subsample.



Figure A-5. Additional samples are acquired from the cut face as needed. One sample is transferred to a plastic bag for screening of volatile organic hydrocarbons. See Figure A-6.



Figure A-6. After the volatile hydrocarbons in the subsample equilibrated with the air in the sealed plastic bag, the concentration of hydrocarbons were measured with an organic vapor meter.



Figure A-7. Each subsample for analysis in the laboratory is introduced into a vial previously prepared with 10 ml of methanol



Figure A-8. The vial was sealed and shaken to disperse the subsample and began the extraction. Note that the empty weight of the vial and cap and the weight of the vial and cap plus methanol were recorded in the laboratory when the vials were made up. When the vial is returned to laboratory it is weighted again to determine the wet weight of the subsample.

APPENDIX B. QUALITY ASSURANCE

The following information documents the data quality of samples collected and analyzed by U.S. EPA from the site in Oklahoma.

The concentration of benzene in the water sample from the site in Oklahoma was analyzed using a modification of EPA Methods 5021A (headspace sampler) and 8260C (GC/MS). The method detection limit was 0.18 µg/L and the quantitation limit was 0.5 µg/L. Benzene was not detected in the method blank. The continuing calibration check was 101% of nominal.

The concentration of benzene and gasoline range organics (GRO TPH) in the methanol extracts were analyzed by EPA Method 5030B, Revision 2 (purge and trap followed by GC/FID). The extract was diluted 1:50 into water prior to analysis. Some samples exceeded the calibration range. These samples were diluted 1:500 and analyzed a second time.

The method detection limit for GRO in the extracts was 155 µg/L; the limit of quantitation was 1250 µg/L. The method detection limit for benzene in the extracts was 6.5 µg/L; the limit of quantitation was 50 µg/L. Neither GRO nor benzene were detected in the method blank. The recovery of GRO in ten continuing calibration checks ranged from 101% to 118%. The recovery of benzene in ten continuing calibration checks ranged from 92% to 114%.

After correcting for dilution of the extract into the water that was analyzed by purge and trap, and for the average weight of sample that was extracted, the limit of quantitation of GRO in the sediment was 9.2 mg/kg and the limit of quantitation of benzene was 0.37 mg/kg. The detection limit of GRO was 2.1 mg/kg and the detection limit of benzene was 0.091 mg/kg.

The relative percent difference between in concentrations of benzene in two sets of field duplicate samples was 2.3% and 1.8%. The relative percent difference between in concentrations of GRO in two sets of field duplicate samples was 0.4% and 0.1%.

APPENDIX C. EQUATIONS FOR STEADY STATE PLUME CALCULATIONS

At steady state,

$$D \frac{d^2c}{dx^2} - v \frac{dc}{dx} - \lambda c = 0$$

where D is the dispersivity, c is concentration, x is distance, v is seepage velocity, and λ is the decay constant. Using the boundary conditions

$$\begin{aligned} c(0) &= c_0 \\ \left. \frac{dc}{dx} \right|_{\infty} &= 0 \end{aligned}$$

The solution for the plume length is

$$x = \frac{2\alpha \ln c/c_0}{1 - \sqrt{1 + \frac{4\lambda\alpha}{v}}}$$

where α is the dispersivity (D=αv), and the dispersivity is presumed independent of plume length (van Genuchten and Alves, 1982). Since dispersivity is known to be scale dependent (Gehlar et al., 1992), an implicit calculation can be substituted linking dispersivity and plume length:

$$x \left(1 - \sqrt{1 + \frac{4f(x)\lambda}{v}} \right) = 2f(x) \ln c/c_0$$

The Xu and Eckstein (1995) regression can give an indication of the scale dependence of dispersivity

$$\alpha = 0.83 [\log x]^{2.414}$$

where α and the plume length, x, are given in meters.



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