
Dilution-Attenuation Factors at Fuel Hydrocarbon Spill Sites

Technical Background Document and Recommendations

Prepared for
**Alaska Statement of Cooperation Working
Group**

December 2006

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Preface

This document was created under the Alaska Statement of Cooperation (SOC), which is an agreement between the Alaska Department of Environmental Conservation (ADEC), the U.S. Environmental Protection Agency (EPA), the Departments of the Army, Air Force, Navy, Military and Veterans Affairs (Army National Guard), Interior, and the Federal Aviation Administration (FAA) and U.S. Coast Guard. The objective of the agreement is to work cooperatively to identify and resolve issues affecting human health and the environment through promoting compliance with environmental laws, preventing pollution, creating partnerships to identify and cleanup contaminants and pollution, promoting training and coordinating with affected Tribes. A subcommittee or “working group” was formed under the SOC to evaluate the characterization and fate and transport of petroleum hydrocarbons spilled in the environment, and the risks posed by petroleum contamination. FAA contracted with Geosphere and CH2M Hill to research the issues and develop eight technical issue papers. The paper titles are listed below. Staff from ADEC, FAA, the Army and Army Corps of Engineers, and the Army National Guard reviewed and provided feedback on the draft papers. These papers provide sound scientific and technical information along with recommendations for use and/or future consideration.

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Statement of Cooperation Working Group Paper Titles

1. Three- and Four-Phase Partitioning of Petroleum Hydrocarbons and Human Health Risk Calculations, Technical Background Report Document and Recommendations
2. Hydrocarbon Characterization for Use in the Hydrocarbon Risk Calculator and Example Characterizations of Selected Alaskan Fuels, Technical Background Document and Recommendations
3. Dilution-Attenuation Factors at Fuel Hydrocarbon Spill Sites, Technical Background Document and Recommendations
4. Maximum Allowable Concentration, Residual Saturation, and Free-Product Mobility, Technical Background Document and Recommendations
5. Groundwater Sampling Techniques for Site Characterization and Hydrocarbon Risk Calculations, Technical Background Document and Recommendations
6. Migration to Indoor Air Calculations for Use in the Hydrocarbon Risk Calculator, Technical Background Document and Recommendations
7. Site Conditions Summary Report for Hydrocarbon Risk Calculations and Site Status Determination, Technical Background Document and Recommendations
8. Proposed Environmental Site Closeout Concepts, Criteria, and Definitions, Technical Background Document and Recommendations

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Acronyms and Abbreviations

ADEC	Alaska Department of Environmental Conservation
AF	attenuation factor
BTEX	benzene, toluene, ethylbenzene and xylene
DAF	dilution-attenuation factor
DF	dilution factor
DRO	diesel-range organics
EPA	U. S. Environmental Protection Agency
FMD	fixed mixing depth
foc	fraction of organic carbon
MCL	maximum contaminant level
µg/L	micrograms per liter
mg/L	milligrams per liter
NAPL	nonaqueous phase liquid
SSL	soil screening level
VMD	variable mixing depth

SECTION 1

Introduction

Dissolved-phase fuel hydrocarbons being transported by groundwater are subject to dilution and attenuation processes as they move through the soil environment. Dilution is caused by hydrodynamic dispersion and results in the spreading and reduction in maximum concentration of a contaminant plume downgradient of the source area, but does not reduce the mass of contaminant in the aquifer. Attenuation of fuel hydrocarbons in groundwater is caused primarily by biodegradation and does reduce the mass of contaminant in the aquifer, which causes a reduction in concentration downgradient of the source area.

The degree of contaminant reduction at any point downgradient of the source area as a result of dilution may be expressed as a “dilution factor” (DF), which is defined as follows:

$$\text{Dilution factor} = \text{concentration in the source area} / \text{concentration at location of interest as a result of dilution processes}$$

The degree of contaminant reduction at any point downgradient of the source area as a result of attenuation may be expressed as an “attenuation factor” (AF), which is defined as follows:

$$\text{Attenuation factor} = \text{concentration in the source area} / \text{concentration at location of interest as a result of attenuation processes}$$

The combined effect of dilution and attenuation may be referred to as the “dilution-attenuation factor” (DAF), which is defined as follows:

$$\text{DAF} = \text{DF} * \text{AF} = \text{concentration in source area} / \text{concentration at downgradient location of interest}$$

As defined above, DFs, AFs, and DAFs all have values equal to or greater than one, and larger DF, AF, and DAF values indicate greater dilution and attenuation. Dilution and attenuation factors are not fixed values – rather, they must be defined and/or measured at a point or over an interval.

DAFs are useful because they relate the dissolved concentration in the source area to the dissolved concentration at downgradient potential receptor locations. DAFs can be used in “forward calculations” to assess the risk at some downgradient location resulting from a known source area concentration, or they can be used in “backward calculations” to assess the dissolved concentration in a source area that presents an acceptable risk at a downgradient receptor location. When making backward calculations, if the source area does not contain nonaqueous phase liquid (NAPL), then the source area dissolved concentration may be related to a source area soil concentration that may be considered the soil cleanup level. If the source area does contain NAPL, then the source area concentration may be used to calculate the allowable mole fraction of the compound of interest in the NAPL (but it cannot be used to back calculate a soil cleanup level).

The Alaska Department of Environmental Conservation (ADEC) uses a DAF to assess whether the soil concentrations are likely to cause groundwater contamination above the maximum contaminant level (MCL) or a risk-based standard (given the DAF assumptions). However, as documented in the ADEC guidance document on cumulative risk (2002), the DAF is not used in the calculation of risk – rather, measured groundwater concentrations are used to assess risk. If the measured groundwater concentrations and the groundwater concentrations predicted using the DAF do not agree, then the true DAF at the site of interest is likely different than the DAF used in the predictive calculation.

Use of a DAF to assess soil cleanup levels requires that the DAF is mathematically formulated to address the compliance point or compliance zone of interest, and that the DAF calculation represents the site conditions and the physical processes occurring at the site. The following site information is needed for the DAF assessment:

- Delineation of the horizontal and vertical extent of the source area relative to the water table (Is the source area partially submerged?)
- Potential receptor location (Is the potential receptor in the source area or downgradient of the source area, and if the exposure point is a drinking water well, what is the screened depth?)
- Attenuation rates based on field data or conservative estimates drawn from the best available field data (What is the dissolved-phase half-life?)

The objectives of this document are as follows:

- Provide background information on dilution and attenuation processes
- Discuss the U.S. Environmental Protection Agency (EPA) and ADEC soil screening DAF calculation
- Introduce an alternative DAF calculation that may better support ADEC groundwater protection objectives
- Use the computer model Modflow to help visualize plumes emanating from source areas

Dilution and Attenuation Processes

2.1 Hydrodynamic Dispersion

Particles being transported by groundwater tend to spread out and become diluted as compared with simple advection. This dilution is caused by hydrodynamic dispersion, which is defined by Freeze and Cherry (1979) as the sum of the processes of (1) molecular diffusion, and (2) mechanical dispersion.

Molecular diffusion is the movement of molecules in response to a concentration gradient and is quantified by Fick's Law. Molecular diffusion may be significant in clay soils, but is typically a minor component of hydrodynamic dispersion at sites with sand and gravel soils and a measurable gradient (that is, where groundwater velocities are significant).

Mechanical dispersion is caused by variations in the flow path and velocity of different advected particles. Figure 1 shows examples of varying particle flow paths, including groundwater flow through larger- and smaller-diameter soil pores (larger pores tend to have higher velocities); along the centerline of connected soil pores versus along the edges of the connected pores (higher velocities occur in the center of the pores); and along longer or more tortuous flow paths. Mechanical dispersion occurs in the direction of groundwater flow (longitudinal dispersion) and transverse to the direction of groundwater flow in both the horizontal and vertical planes. The tendency of a soil to cause or promote dispersion is quantified as the "dispersivity" of the soil. Dispersivity values have units of length, and field and laboratory studies have shown that longitudinal dispersivity values vary with the transport length. That is, dispersivity values calculated from laboratory studies commonly are on the order of centimeters, while dispersivity values calculated from field studies are on the order of tens or hundreds of meters (Gelher, 1986; Bedient, et al., 1999). The higher dispersivity values measured in field studies are the result of an increase in the heterogeneity of the soils at the field scale as compared to the lab scale. Horizontal transverse dispersivity or lateral dispersivity values are commonly 1 to 2 orders of magnitude lower than longitudinal dispersivity, and vertical dispersivity is commonly 2 to 3 orders of magnitude lower than longitudinal dispersivity. Longitudinal dispersion affects the arrival time of the plume, but does not change the long-term concentration of the plume, given an infinite source assumption (that is, the source concentration does not decrease through time). Horizontal transverse or lateral dispersion and vertical dispersion tend to increase the width and depth of the dissolved plume and simultaneously decrease the maximum dissolved concentration.

Field measurements of the dissolved concentration downgradient of a source area may be readily used to calculate a DAF; however, assessing the contribution of dilution versus attenuation (biodegradation) to the DAF requires more detailed studies, which may include conducting dye or tracer tests and/or measuring changes in the concentration of electron acceptor or metabolic byproducts (dissolved oxygen, sulfate ferrous iron, methane, etc.) along the plume length.

2.2 Attenuation/Biodegradation

The attenuation of fuel hydrocarbons is a result primarily of biodegradation, and the biodegradation of fuel hydrocarbons in dissolved phase plumes is commonly described as either an instantaneous aerobic reaction, or as a first-order anaerobic reaction. In an instantaneous reaction the oxygen and hydrocarbon in a unit volume of aquifer react (are consumed by microbes) in relatively short time compared to the groundwater velocity. The aerobic biodegradation/reaction continues until either all of the oxygen or all of the hydrocarbon in the unit volume of aquifer is consumed. In first-order reactions, the rate of reaction is a function of the dissolved concentration. The first-order rate equation is as follows:

$$C = C_o * e^{-kt}$$

Where: C = concentration at time t (mg/L)
 C_o = original concentration (mg/L)
 k = first-order reaction rate constant
 t = time (days)

The time factor in the above equation may be related to a transport distance, given a groundwater velocity:

$$\text{Transport distance (ft)} = \text{groundwater velocity (ft/day)} * \text{time (days)}$$

or

$$\text{time (days)} = \text{transport distance (ft)} / \text{groundwater velocity (ft/day)}$$

The biodegradation reaction rate constant may be expressed as a dissolved phase half-life as follows:

$$\text{Half-life (days)} = \ln 0.5 / -k = -0.693 / k$$

Numerous studies of biodegradation in dissolved plumes have been conducted in the last 10 or more years, and rates of biodegradation from a number of these studies have been summarized in a paper by Suarez and Rafai (1999). Table 1 presents selected first-order biodegradation rates from their paper. The biodegradation rates are presented as rate constants and as half-lives (the time required for half of the dissolved contaminant mass to degrade). The table shows that 1) benzene, toluene, ethylbenzene, and total xylenes (BTEX) compounds are rarely recalcitrant (resistant to biodegradation) in either aerobic or anaerobic environments; 2) aerobic biodegradation rates tend to be higher than anaerobic rates for benzene, ethylbenzene, and xylene, while toluene has similar aerobic and anaerobic rates; and 3) given an anaerobic environment, benzene typically degrades most slowly, followed by xylene and ethylbenzene (similar rates), and then by toluene, with a relatively high biodegradation rate. (Diesel-range organics [DRO] aromatics and aliphatics are not listed on the table, presumably because a body of field data was not available to the authors). Note that source areas and downgradient dissolved plumes are typically anaerobic, because when hydrocarbon and dissolved oxygen are both present, the dissolved oxygen is

consumed relatively rapidly in biodegradation (aerobic biodegradation in the saturated zone is often described as an instantaneous reaction).

SECTION 3

EPA and ADEC Dilution Model and Soil Screening Levels

The EPA Soil Screening Guidance Technical Background Document (1996) describes a dilution model that was evaluated in support of the DAF that was used in the calculation of EPA soil screening levels (SSLs). Note that the EPA did not use the dilution model in their calculation of SSLs; instead, the EPA elected to assume a standard DAF of 20 based on a weight of evidence approach. The EPA also conducted Monte Carlo simulations that indicated the DAF of 20 would be protective of drinking water in a thick aquifer 90 to 95 percent of the time. Also note that the EPA SSL approach has been used to back calculate SSLs that differentiate sites that do not need further study from those that do need further study. (The EPA SSLs are not cleanup levels.) The ADEC subsequently borrowed and slightly modified the EPA dilution model to develop the Table B1 and B2 migration-to-groundwater soil cleanup levels.

The DAF equation used by the ADEC is described in this document as a “variable mixing depth” (VMD) dilution attenuation factor (DAF) equation, or VMD DAF equation, because the mixing depth is allowed to vary as a function of source length. Conceptual site diagrams showing the source zone, mixing zone, groundwater flow directions, infiltration, and hydrodynamic dispersion considered in the VMD DAF model are provided in Figures 2 and 3. Assumptions of the EPA and ADEC dilution attenuation model are as follows:

- The source is infinite (that is, the dissolved concentration emanating from the source area does not decrease through time).
- The source is entirely within the vadose zone (no portion of the source is submerged at any time of the year).
- Infiltrating precipitation is in equilibrium with the source and carries dissolved contaminants to the water table.
- No dilution or attenuation occurs within the vadose zone.
- The DAF applies at the downgradient edge of the source area.
- The DAF applies over a “mixing zone” depth, which is a characterization of the maximum depth of contaminant migration at the downgradient edge of the source area (that is, contaminants from the source zone will not be carried below the mixing zone depth at the downgradient edge of the source area – contaminants may be carried below the mixing zone depth downgradient of the source area).
- *The DAF relates the average concentration within the mixing zone depth to the source concentration. Note that shallow portions of the mixing zone will be above this average concentration and the deeper portions of the mixing zone will be below the average concentration.*

The EPA dilution model is based on a water balance in which the volume of water flowing through a mixing zone is compared to the volume of groundwater flowing through the source zone (see Figure 3). The EPA provides several different expressions of this concept, including the following, which is based on a Summers box model:

$$C_w = (Q_p * C_p) / (Q_p + Q_a)$$

Where: C_w = groundwater contaminant concentration

C_p = infiltration leachate concentration

Q_p = infiltration (per unit width) = $I * L$

I = infiltration rate

L = length of source area

Q_a = aquifer flow rate (per unit width) = $K * i * d$

K = hydraulic conductivity

i = hydraulic gradient

d = mixing zone depth

1/ dilution factor = $Q_p / (Q_p + Q_a)$

Dilution factor = $(Q_p + Q_a) / Q_p$

Dilution factor = $1 + (K * i * d / I * L)$

Note that the last equation is ADEC Equation 12 from the Guidance on Cleanup Level Calculations (2004). In the equation the term “ $K * i * d$ ” is the volume of groundwater flowing through a unit width of the mixing zone, and the term $I * L$ is the volume of infiltrating precipitation (that is, groundwater at the downgradient edge of the source area) that flowed through the contaminated source zone.

In the EPA SSL documents, the mixing zone depth is calculated as the sum of the depth of particle transport caused by the downward velocity of infiltrating precipitation, and the depth of particle transport by vertical dispersion, as follows:

$$d = d_{av} + d_{iv} = \text{depth of mixing zone}$$

Where: d_{av} = depth of mixing zone to vertical dispersion

$$d_{av} = (0.0112 L^2)^{0.5}$$

L = source zone length

$d_{iv} = d_a \{1 - \exp [(-LI)/(Kd_a)]\}$ = depth of mixing zone to vertical velocity of infiltration

d_a = thickness of aquifer

L = source zone length

I = infiltration

K= hydraulic conductivity

i = hydraulic gradient

$$d = (0.0112 L^2)^{0.5} + d_a \{1 - \exp [(-LI)/(Kid_a)]\}$$

Note that the last equation is ADEC Equation 13 from the Guidance on Cleanup Level Calculations (2004). Because the existing ADEC DF model equation has a VMD, which increases as the source length increases, the equation may be referred to as the VMD DF equation.

The EPA and ADEC mixing zone depth and DF calculation has been solved for a number of example aquifer thicknesses and source lengths, and the results are graphed in Figures 4 through 6. As shown in Figure 4, the mixing zone depth (or thickness) increases as the source zone length increases, up to about the point that the mixing zone depth equals the aquifer thickness (the mixing zone depth cannot be greater than the aquifer thickness). As shown in both Figures 5 and 6, the DF does not significantly change as the source length increases or mixing zone increases, until the mixing zone depth approaches the aquifer thickness (recall that the source length and mixing zone depths are linked).

The DF calculated by the VMD DF may be used to back calculate the dissolved concentration allowed in the source zone as follows:

$$\text{MCL or risk-based concentration at compliance point} * (\text{DF} * \text{AF}) = \text{allowable source zone dissolved concentration}$$

The VMD DF equation does not include attenuation. ADEC chose to account for the effect of attenuation by adding a value of 10 to the calculated DF. Note that, by definition, the DF and AF should be multiplied (not added) to calculate a DAF. The effect of multiplying, instead of adding, the DF and AF becomes important when site-specific DFs are calculated. Given that the ADEC default DAF is 13.3 and the default DF is 3.3, a default AF of about 4 may be readily calculated ($\text{AF} = \text{DAF}/\text{DF} = 13.3/3.3 = 4.0303$).

A sensitivity analysis was performed to show how varying the VMD DAF equation input parameters changed the calculated migration-to-groundwater SSL. In the sensitivity analysis one input parameter was changed while the other input parameters were held constant at the ADEC default site condition values. The equation input parameters and calculated soil cleanup level are shown in Table 2. Yellow highlights show the set of input values which were varied from the assumed default condition, while gray highlights show the calculated SSL (in milligrams per kilogram) and the variability in the SSL given the input parameters (highest screening level divided by the lowest screening level). The effect of changes in the hydraulic conductivity, infiltration rate, fraction of organic carbon (foc), soil moisture content and AF on the migration-to-groundwater SSL are graphed in Figures 7 through 11. Table 2 and Figures 7 through 11 show that SSLs and/or soil cleanup levels calculated using the VMD DAF equation are relatively sensitive to the hydraulic conductivity, AF, infiltration rate, and foc input values; and less sensitive to variables such as soil moisture content, bulk density, and source length.

Note that the effect of variation in the VMD DAF equation input values is complex. For example a site with a lower infiltration rate (such as $\frac{1}{4}$ the default value) and higher hydraulic conductivity value (such as 10x the default value) has a DAF 16 times higher than the default DAF. The impact of varying several VMD DAF equation input parameters simultaneously is shown in several example calculations at the bottom of Table 2. The ADEC default assumptions are shown in Example 1. Example 2 represents a hypothetical glacial outwash soil in a relatively dry area (such as Delta or Fairwell). Example 3 represents clean fluvial or marine sand in an area with high dissolved oxygen levels in the groundwater (Cantwell, Gold Creek, or Tok). Example 4 could be lacustrine silt in the Copper River Basin. As shown in the example calculation Nos. 2 and 3, very reasonable input parameters may yield DAFs that are orders of magnitude higher than the default DAF value. Given that many Alaskan sites have higher hydraulic conductivities, gradients, and lower net infiltration rates than those in the ADEC default site condition assumptions, soil cleanup levels calculated with the default site conditions may be orders of magnitude lower than necessary to protect human health via the migration-to-groundwater route. The Example 4 calculation shows that some site conditions may yield migration to groundwater soil cleanup levels below the values calculated with the ADEC default site conditions. (The Table B1 values may not be protective of the migration to groundwater route.)

These example DAF calculations show that at sites where conditions are known to vary from the default conditions, the risk posed by the migration-to-groundwater route should be evaluated using the site specific input parameters. In addition, the Table B1 and B2 values should be thought of as "soil screening levels" and not as "soil cleanup levels." According to the EPA, sites with concentrations above soil screening levels require additional study to assess if they present an unacceptable risk, while sites with concentrations below soil screening levels are assumed to have acceptable risks and do not require additional study.

SECTION 4

Limitations of the EPA and ADEC Dilution Attenuation Factor Calculation

The VMD DAF equation as described above may not be the best tool for assessing the impact of contaminated soils on groundwater (the migration to groundwater route) because of several limitations, as follows:

- The VMD DAF equation only addresses vadose zone sources. At most contaminated sites in Alaska, NAPL extends into the saturated zone for at least part of the year. (A smear zone exists and is submerged during periods of high groundwater at most Alaska sites.)
- The VMD DAF equation yields the same DF value for both small and large sites, even though large sites may contribute orders of magnitude more hydrocarbon mass to the saturated zone than small sites
- The VMD DAF equation conceptually allows a significant thickness of the aquifer to be contaminated at a large site with a thick aquifer. For example, sites on the Chena or Tanana River floodplains at Fairbanks with a source length of 600 feet have a mixing zone thickness of about 100 feet, and a significant portion of this mixing zone thickness would be expected to exceed the risk-based groundwater concentration. Given that the VMD DAF equation is representative of site conditions, recall that the average concentration in the mixing zone will equal the risk-based concentration and the shallow portion of the aquifer will exceed the risk-based concentration. (Note that Title 18, Chapter 75, of the *Alaska Administrative Code* (2005) states that all portions of the aquifer must meet the Table C groundwater quality criteria and that meeting these criteria requires a DAF of 1. A DAF of 1 will reduce Table B1 and B2 soil cleanup levels by more than an order of magnitude, suggesting that remediation may be needed at many sites that do not pose a true human health risk.)
- The VMD DAF equation as currently used has a default attenuation factor that is the same for all compounds at all sites. Published literature on intrinsic biodegradation shows that organic compounds degrade at very different rates. Toluene appears to biodegrade readily, and a very high attenuation factor may be appropriate. Benzene typically degrades at much lower rates than toluene; therefore, a lower attenuation factor is likely appropriate. Finally, some compounds such as chlorinated solvents appear to be very recalcitrant; therefore, an attenuation factor of 1 may be appropriate unless biodegradation is demonstrated on a site-specific basis.

SECTION 5

Proposed Alternative Dilution Factor Calculation

Many limitations of the VMD DF equation may be mitigated by using a Summers box model calculation that assumes a fixed mixing zone depth, accounts for the presence of NAPL in the seasonally saturated zone, and allows representative biodegradation. A potential alternative DAF model based on a mass balance is as follows:

$$DAF = C_o / C_a$$

Where: C_o = dissolved concentration in equilibrium with NAPL

C_a = average concentration in fixed mixing zone

$$C_a = ((Q_s * C_o) + (Q_i * C_i)) / Q_t$$

Where: Q_s = groundwater flow through saturated source zone = hydraulic conductivity * gradient * source saturated thickness (up to the limit of the mixing zone depth)

C_o = dissolved concentration in equilibrium with NAPL (not subject to biodegradation)

Q_i = flow from bottom of source zone that passes through the mixing zone = infiltration rate * source length (up to the limit of $Q_t - Q_s$)

C_i = concentration in flow from bottom of source area at mixing zone location (subject to biodegradation) = $C_o * e^{-kt}$, or $C_i = C_o / \text{fixed attenuation default factor}$ (if half-life and rate constant data not available)

Q_t = total flow through fixed-depth mixing zone = hydraulic conductivity * gradient * fixed mixing zone depth

Figure 12 shows the conceptual site conditions associated with this equation. In concept, the mixing zone is a fixed depth zone (the same for all sites regardless of source length) or plane (it is thin relative to the groundwater velocity), located at the downgradient edge of the source area (represented by the thick black line at the downgradient edge of the source area shown in Figure 12). Because the proposed equation uses a fixed mixing depth, it is called the "FMD DAF equation" (fixed mixing depth dilution attenuation factor). A mixing zone depth of 18 feet below the low water table (or the thickness of the aquifer, whichever is less) is recommended for the following reasons:

- Most drinking water wells are not expected to be screened entirely within 18 feet of the water table. (Deeper screens are expected, and if the well screens are deeper than 18 feet, then the calculation is conservative.)

- The 18-foot (5.5-meter) depth matches the ADEC default assumption for the mixing zone depth.
- Monitoring wells are typically installed with screens extending about 5 to 15 feet below the water table; therefore, the monitoring wells will be measuring the dissolved concentrations in the depth interval in which the DAF is applicable.

Groundwater leaving the site through this fixed mixing zone may conceptually follow three flow paths designated Q1, Q2, and Q3 in Figure 12 and described as follows:

- Q1 represents groundwater that flowed from the submerged portion of the source directly into the mixing zone.
- Q2 represents groundwater derived from infiltrating precipitation that flowed from the bottom of the vadose or saturated zone portions of the NAPL source area. (In the saturated zone, flow emanating from the bottom of the source would be that flow deflected downward by the infiltrating precipitation.)
- Q3 represents groundwater that flowed beneath the source zone without being affected by the source.

The impact of hydrodynamic dispersion is ignored in this model, and the dilution process is conceptually caused by the mixing of groundwater which has contacted the source zone with groundwater that has not contacted the source zone. Groundwater that exits the site through the saturated source zone directly into the mixing zone will be in equilibrium with the NAPL source and will have a DAF of 1. Groundwater that passes through a portion of the source zone but is deflected out of the bottom of the source zone by infiltrating precipitation will be in equilibrium with the source zone soils as it leaves the source zone, but will be subject to attenuation (biodegradation) below the source as it travels to the mixing zone at the downgradient edge of the source area. Given that biodegradation may be described using a first-order rate function, the groundwater that emanates from the upgradient portions of the source zone follows a longer flow path and takes a longer period of time to reach the mixing zone; therefore this groundwater will experience more biodegradation. Groundwater that exits the site within the fixed-depth mixing zone, but does not encounter contaminated soils is considered to be uncontaminated. (As indicated above, hydrodynamic dispersion is not considered.)

If seasonal groundwater fluctuation occurs at a site with a NAPL-contaminated smear zone, then the DAF will be lower during periods of high groundwater when more of the NAPL-contaminated soil source zone is submerged. Therefore, if the DAF is being used to help assess soil cleanup levels, then the DAF calculation should be made by using an estimate of the saturated source thickness representative of high groundwater conditions. Also, the DAF calculation is not conservative for drinking water wells located in the source zone and with screened intervals less than 18 feet below the water table. If these conditions exist (and they might at sites with driven well points), then the “fixed” mixing zone depth should be adjusted to match the depth of the screened interval.

An Excel spreadsheet has been developed to represent the dilution and attenuation processes envisioned in the fixed mixing depth DAF model. Input parameters include the following:

- Depth of the NAPL source zone below the average seasonal low groundwater level
- Depth of the NAPL source zone below the average seasonal high groundwater level
- Seasonal water table fluctuation
- Gradient, hydraulic conductivity and effective porosity data
- Half-life or rate constant values

The spreadsheet divides the flow from the bottom of the source zone that is within the mixing zone depth into 10 flow tubes and characterizes biodegradation in the flow tubes by using a first-order function ($C = C_0 * e^{-kt}$) or uses a default attenuation rate if half-life or rate constant data are not available. When representing biodegradation with a first-order rate function, the amount of attenuation that occurs is not a simple factor of 2, 3, or 10, but rather is a function of reaction rate constant, travel distance, hydraulic conductivity, and gradient. Note that mixing zone depth is fixed based on the seasonal low of the water table level and that, as the water table rises, the thickness of the mixing zone increases. The FMD DAF spreadsheet calculates the concentration and DAF that would be observed in a monitoring well installed at the downgradient edge of the source and screened from the depth of fixed mixing zone (~18 feet or 5.5 meters below the seasonal low-water level) to the seasonal high-groundwater level. The FMD DAF spreadsheet has been integrated in to a version of the "hydrocarbon risk calculator." Note that migration to groundwater calculations are best used to help understand the relationship between soil source area concentrations and dissolved concentrations in a mixing zone, but are not well suited for establishing generic soil cleanup levels.

A sensitivity analysis was performed to show how varying the FMD DAF equation input parameters changed the calculated DAF values. In the sensitivity analysis, one input parameter or a pair of input parameters was changed while the other input parameters were held constant. The equation input parameters and calculated DAF values are shown in Tables 3 through 7. Yellow highlights show the set of input values that were varied from the assumed default condition, and gray highlights show the calculated DAF at the high-water condition given the input parameters. The effect of changes in the source length, saturated zone source thickness, biodegradation half-life, infiltration rate, and groundwater velocity are graphed in Figures 13 through 16.

Tables 3 and 4 and Figures 13A and 13B show how the DAF changes as the source length, saturated source thicknesses, and biodegradation half-lives change. Figure 13A has a very long half-life (1 million days) resulting in biodegradation that is essentially zero, and dilution is the only DAF process occurring. Figure 13A shows the following:

- Short sources have higher DAFs than long sources. (This finding appears to be conceptually correct, representative of field conditions at sites with recalcitrant contaminants, correlative with field measurements, and address one of the problems associated with the current VMD DAF equation.)
- Submerged sources have lower DAFs than do vadose zone sources, and the greater the saturated thickness, the lower the DAF. (This finding appears to be conceptually correct,

representative of field conditions, correlative with field measurements, and addresses one of the problems associated with the current VMD DAF equation.)

Figure 13B portrays a site with a contaminant half-life (25 days, typical of xylene) that allows biodegradation to contribute to the dilution-attenuation processes. Figure 13B shows the following:

- Submerged sources have lower DAFs than do vadose zone sources, and the greater the saturated thickness, the lower the DAF.
- As the source length increases at sites with active biodegradation, the biodegradation process consumes a high proportion of the dissolved-phase hydrocarbon below the NAPL source zone, so that the effect of longer sources is limited, and the DAF becomes essentially a function of the contaminant mass contributed to the aquifer in the submerged portion of the source and by infiltration close to the mixing zone. (This finding appears representative of field conditions, is correlative with field measurements and more sophisticated models such as Modflow and MT3D, and is likely a conceptual improvement on the current VMD DAF equation.)

Table 5 and Figure 14 show the effect of the biodegradation half-life on the DAF for different thicknesses of the saturated source zone. (All other site conditions match the ADEC default assumptions.) The example calculations indicate that the biodegradation half-life greatly influences the DAF for vadose zone sources but has a lesser impact on saturated sources. In the example calculations, when sources are in the smear zone, the DAF increases as the half-life decreases, but the saturated source zone thickness controls the overall DAF value.

Table 6 and Figure 15A and 15B show the effect of changes in the infiltration rate and biodegradation half-life on the DAF given different saturated source zone thicknesses. Increased infiltration rates cause increased amounts of water to emanate from the bottom of the source zone so that, at high infiltration rates, all of the water within the mixing zone depth has contacted the source zone. In Figure 15A, the half-life is 1 million days; therefore, biodegradation/attenuation is insignificant and dilution is the primary DAF process. Figure 15A clearly shows that as the infiltration rate increases, the DAF value converges on 1 for all saturated source thicknesses. In contrast, as shown in Figure 15B when the half-life is 25 days, biodegradation of dissolved contaminants below the source zone reduces or essentially eliminates the impact of increasing infiltration rates so that the DAF value becomes a simple function of the saturated source thickness.

Table 7 and Figures 16A and 16B show the effect of changes in the groundwater velocity and biodegradation half-life on the DAF given different saturated source zone thicknesses. Recall that the groundwater Darcy velocity is the product of the hydraulic conductivity and the gradient ($V = K \cdot i$), and that the advective velocity is the Darcy velocity divided by the effective porosity. Increased groundwater velocities tend to dilute the infiltrating precipitation (resulting in higher DF values) and to also transport the groundwater emanating from the bottom of the source zone to the mixing zone faster, allowing less time for biodegradation (which decreases the attenuation rate). In Figure 16A, the half-life is 1 million days; therefore, biodegradation/attenuation is insignificant and dilution is the primary DAF process. Figure 16A shows that for vadose zone sources increased groundwater velocities result in linearly increasing dilution factors. Figure 16A also shows

that for saturated zone source areas, as the groundwater velocity increases, contaminants transported into the mixing zone by infiltrating precipitation are diluted to the point that the DAF value becomes a simple function of the saturated source thickness. Figure 16B shows the effect of groundwater velocity on the DAF when the dissolved-phase half-life is 25 days and biodegradation contributes to the DAF. Figure 16B shows that for saturated zone sources when the half-life is 25 days, biodegradation of dissolved contaminants below the source zone reduces or essentially eliminates the impact of limited dilution at low groundwater velocities so that the DAF value becomes a simple function of the saturated source thickness. Figure 16B also shows that at sites with vadose zone sources and significant biodegradation rates, the effect of changes in groundwater velocity on the DAF may be complex--that is, increasing groundwater velocities increase the dilution factor but simultaneously decrease the attenuation factor.

Modflow Simulations of Dilution and Attenuation

The site conditions assumed in the ADEC default migration-to-groundwater calculation and several related scenarios were modeled in Modflow and MT3D (Visual Modflow Version 4.0) to help visualize the processes and results of the VMD DAF equation and the new proposed FMD DAF equation. The Modflow model used in the simulation is a two-dimensional model that constitutes a longitudinal cross-section through the source zone. The model domain is 1,000 feet long (137 cells) and has a thickness of 400 feet (40 cells). Boundary conditions include constant head boundaries at the upgradient and downgradient ends of the model, a no-flow boundary at the base of the model, and a recharge boundary across the top of the model. The source was simulated as a constant concentration recharge boundary. All simulations used ADEC default site conditions for the infiltration rate (0.13 meters per year), hydraulic conductivity (876 meters per year), and a gradient of about 0.002. (Note that as configured, the gradient changes across the width of the model, but at the downgradient edge of the source area, the gradient is about 0.002). The Modflow simulations portray varying source lengths, reaction rate constants, and aquifer thicknesses. Steady-state flow was assumed, and the transport simulation period was 10 or 20 years (at which time the transport conditions were also steady-state).

6.1 Modflow Simulations of Dilution for Source Areas of Different Sizes

The first set of Modflow simulations demonstrates the impact of source zone length on the depth of contaminant penetration into the aquifer and illustrates how the VMD DAF equation and proposed FMD DAF equations provide different DFs (when biodegradation is insignificant) and consequently different soil cleanup levels.

Modflow Simulation DF1 – Default Conditions. The first model scenario assumed the ADEC default source zone length of 32 meters (105 feet), an aquifer thickness of 10 meters, and a reaction rate constant of 0 (so that no biodegradation occurs). Therefore, dilution is the only DAF process. (Subsequent model runs have different aquifer thicknesses and source lengths.) The source zone was assigned a dissolved-phase benzene concentration of 0.0165 mg/L, which is equal to the benzene MCL multiplied by the ADEC default DF of 3.3. The results of the model are presented in Table 8 and a close-up view of the downgradient edge of the source area (Figure 17). Table 8 summarizes results from four different Modflow model runs. The top part of Table 8 lists the input parameters for the model and highlights the source length and aquifer thickness values, which vary from the default assumptions in subsequent simulations. The middle part of Table 8 shows the mixing zone depth and DF calculated from the current VMD DAF equation, and the mixing zone depth and DF calculated from the proposed alternative FMD DAF equation (without biodegradation). The DFs calculated from the results of the Modflow runs are highlighted in blue. The bottom

portion of Table 8 presents dissolved concentrations in the shallow portion of the aquifer as calculated in the Modflow output files. Aquifer layers with benzene concentrations exceeding the benzene MCL are highlighted in yellow. The thicknesses of the model layers are shown toward the left. (Most shallow layers are 1 foot thick.) Figure 17 shows the source zone in pink and the uncontaminated vadose zone in green. Below the green and pink blocks is the saturated aquifer, with groundwater flow pathways shown as green lines with arrows at 100-day travel time increments. Benzene concentration contours are shown as brown lines and are at 5-microgram per liter ($\mu\text{g}/\text{L}$) increments. (The first contour is at 5 $\mu\text{g}/\text{L}$.) In addition, increasing benzene concentrations are highlighted in increasingly warm colors. The lowest color highlight is at 0.001 mg/L. (The aquifer with benzene concentrations below 1 $\mu\text{g}/\text{L}$ is white.) Model grid cells are shown as black lines. (Saturated zone layers 2 through 12 are 1 foot thick.)

In Figure 17, note that the flow pathways are not parallel to the water table but rather dip downward. This downward path is caused by infiltration displacing the groundwater downward. The Modflow simulation also shows benzene present outside the groundwater flow pathways. This spreading of the plume is the result of hydrodynamic dispersion. Given equal flow within each depth increment, the average dissolved concentration and DF are readily calculated within the mixing zone depth of 5.5 meters (18 feet). The source concentration divided by the average concentration within the mixing zone yields a dilution factor of 3.2. This value is very close to the current VMD DAF equation and proposed new FMD DAF equation results of 3.3. (The Modflow DAF results should not be expected to agree perfectly with the DAF calculated by the VMD DAF equation and proposed FMD DAF equations for several reasons, including the following: the Modflow simulations assume that vertical conductivity is 10 percent of horizontal conductivity; hydrodynamic dispersion is not considered in the FMD DAF, and the math used in the numerical model is different than that used in the simple DAF equations. However, the Modflow results are thought to be valuable to help visualize the DAF processes and assess whether the VMD and FMD DAF equations are providing valuable characterizations of the DAF processes.) Note that Figure 17 and Table 8 show that benzene concentrations within the mixing zone exceed the benzene MCL in the shallow portion of the mixing zone (benzene exceeds the MCL in about the top 9 feet of the aquifer), although the average concentration within the mixing zone is approximately equal to the MCL.

Modflow Simulation DF2—Thick Aquifer. The second Modflow simulation assumes that the aquifer is relatively thick (118 meters; 390 feet), and that no biodegradation occurs. All other site conditions match the ADEC default conditions. The model results, shown in Figure 18 and Table 8, indicate that the presence of the thick aquifer does not significantly affect the DF (as expected). The VMD DF equation calculates a DF of 3.3 and Modflow results indicate a DF of about 3.0. Figure 18 and Table 8 show that benzene concentrations within the mixing zone exceed the benzene MCL in the about the top 9 feet of the aquifer, although the average concentration within the mixing zone is approximately equal to the MCL.

Modflow Simulation DF3—Long Source Area. The third Modflow simulation assumes that the source zone is relatively long (91 meters; 300 feet) compared to the default assumption (32 meters [105 feet]) and that the aquifer is thick (390 feet). All other site conditions match the ADEC default conditions. The model results are shown in Figure 19 and Table 8. As

shown in Table 8, the current VMD DAF equation calculates a mixing depth of 53 feet and a DF of 3.4 within this depth. The Modflow model results indicate the DF in the top 53 feet of the aquifer was about 2.7. The proposed new FMD DAF equation yields a DF value of 1 within the top 18 feet of the aquifer and the Modflow results show the DF within the top 18 feet of the aquifer was about 1.5. The Modflow results show that benzene is present at concentrations above 0.005 mg/L about 32 feet below the water table (see Figure 19). Note that this depth of benzene contamination may be expected given the current VMD DAF equation and the use the DF equation to calculate soil cleanup levels (that is, if the dilution processes occur as they are characterized in the VMD DAF equation, the site conditions match the default site conditions, and the site soils are cleaned up to a level calculated using ADEC equation 11 with an AF of zero, then a significant thickness of the aquifer [30+ feet] may be contaminated above the benzene MCL, but the average benzene concentration within the 53-foot mixing zone depth will be about 5 µg/L).

Modflow Simulation DF4 – Short Source Area. The fourth Modflow simulation is identical to simulations 2 and 3 except that the source zone is relatively short (6.1 meters; 20 feet). Because the source area is short, the current VMD DAF equation yields a mixing depth of 3.6 feet and a DF of 3.4 within this depth. The Modflow model results (Table 8 and Figure 20) indicate the DF in the top 3.2 feet of the aquifer was about 3.5. The proposed new FMD DAF equation yields a DF value of 13.2 within the top 18 feet of the aquifer and the Modflow results show that DF within the top 18 feet of the aquifer was about 17. The Modflow results show that benzene is present at concentrations above 0.005mg/L about 2.2 feet below the water table. Again, realize that the current VMD DAF equation calculates the same soil cleanup level for the large source area in the above example as it does for the small source area in this example, even though the large source area impacts the top 32 feet of the aquifer while the small source area impacts only the top 2 feet of the aquifer (above MCLs).

Conclusions Regarding the Effect of Varying Source Length on Dilution Factors. The existing VMD DAF equation allows the mixing zone depth to increase as the source length increases. In turn, the relatively deep mixing zone allows a significant thickness of the aquifer to be impacted by hydrocarbons, as shown in the simulation with the 300-foot-long source. The depth of aquifer impacted by dissolved hydrocarbons may readily be limited by adopting a fixed mixing zone depth. The fixed mixing zone depth would also yield a higher DF for very short sources, which appears appropriate given the limited depth of aquifer impacted in the Modflow simulation with the 20-foot-long source.

6.2 Modflow Simulations of the Effect of Differing Biodegradation Rates on DAF Values

Recall that most anaerobic biodegradation is described as a first-order reaction, that the half-lives of the BTEX compounds vary greatly, and that benzene has been reported as having an average anaerobic half-life of about 231 days (see Table 1; Suarez and Rifai, 1999). The second set of Modflow simulations illustrates the effect of the biodegradation rate on the DAF value by modeling plumes using an average biodegradation rate (half-life of 231 days), a relatively high biodegradation rate (half-life of 115 days), a higher biodegradation (half-life of 58 days) and a relatively slow biodegradation rate (half-life of 461 days). All these

simulations assume that ADEC default site conditions exist (the only variable is the biodegradation rate). The infiltrating precipitation has a dissolved phase benzene concentration of 0.0665 mg/L (66.5 µg/L), which is equal to the benzene MCL multiplied by the ADEC default DAF value of 13.3 (the infiltration concentration in the preceding examples was 16.5 µg/L). The results of the simulations are displayed in Table 9 and in Figures 21 through 24. The top part of Table 9 lists the input parameters for the model and highlights in pink the half-life and reaction rate values, which vary in subsequent simulations. The middle part of Table 9 shows the mixing zone depth and DF calculated from the current VMD DAF equation, and the mixing zone depth and DAF calculated from the proposed alternative FMD DAF equation. The DAFs calculated from the results of the Modflow runs are highlighted in blue. The bottom portion of Table 9 presents dissolved concentrations in the shallow portion of the aquifer. The thicknesses of the model layers are shown toward the left. (Most shallow layers are 1 foot thick.) Aquifer layers with benzene concentrations exceeding the benzene MCL are highlighted in yellow.

Modflow Simulation DAF1a – Average Biodegradation Rate. In this Modflow simulation all site conditions match the ADEC default conditions and the benzene biodegradation half-life was set at 231 days (equal to a reaction rate constant of 0.003/day), which is the average value reported by Suarez and Rifai (1999). The model results are shown in Figure 21 and Table 9. The VMD DAF equation calculates a mixing zone depth of 18 feet and a DAF of 13.3 within this depth. The Modflow results indicate a DAF of about 9 within the mixing zone depth. The proposed new FMD DAF equation with a half-life of 231 days calculates a DAF of 17. In the Modflow output, benzene concentrations exceed the benzene MCL in about the top 8 feet of the aquifer, and the average concentration within the mixing zone is slightly above the MCL.

Modflow Simulation DAF1b – High Biodegradation Rate. In this Modflow simulation all site conditions match the ADEC default conditions and the benzene biodegradation half-life was set at 115 days (equal to a reaction rate constant of 0.006/day), which is twice the average value reported by Suarez and Rifai (1999). The model results are shown in Figure 22 and Table 9. As indicated previously, the ADEC VMD DAF equation calculates a mixing zone depth of 18 feet and a DAF of 13.3 within this depth. The Modflow results indicate a DAF of about 19 within this mixing zone depth because of the higher biodegradation rate. The proposed new FMD DAF equation with a half-life of 115 days calculates a DAF of 30. Benzene concentrations exceed the benzene MCL in about the top 5 feet of the aquifer, and the average concentration within the mixing zone is below the MCL.

Modflow Simulation DAF1c – Very High Biodegradation Rate. In this Modflow simulation all site conditions match the ADEC default conditions and the benzene biodegradation half-life was set at 58 days (equal to a reaction rate constant of 0.012/day), which is four times the average rate reported by Suarez and Rifai (1999). The model results are shown in Figure 23 and Table 9. As indicated previously, the VMD DAF equation calculates a mixing zone depth of 18 feet and a DAF of 13.3 within this depth. The Modflow results indicate a DAF of about 41 within this mixing zone depth because of the higher biodegradation rate. The proposed new FMD DAF equation with a half-life of 58 days calculates a DAF of 53. In the Modflow results benzene concentrations exceed the benzene MCL in about the top 3 feet of the aquifer, and the average concentration within the mixing zone is below the MCL.

Modflow Simulation DAF1d – Low Biodegradation Rate. In this Modflow simulation all site conditions match the ADEC default conditions and the benzene biodegradation half-life was set at 462 days (equal to a reaction rate constant of 0.0015/day), which is half the average rate reported by Suarez and Rifai (1999). The model results are shown in Figure 24 and Table 9. As indicated previously, the VMD DAF equation calculates a mixing zone depth of 18 feet and a DAF of 13.3 within this depth. The Modflow results indicate a DAF of only about 6 within this mixing zone depth because of the low biodegradation rate. The proposed new FMD DAF equation with a half-life of 462 days calculates a DAF of 9. In this scenario benzene concentrations exceed the benzene MCL in about the top 9 feet of the aquifer, and the average concentration within the mixing zone is above the MCL.

Varying Biodegradation Rate Conclusions. The four Modflow simulations, which show the effect of the biodegradation rate on the DAF, suggest that the ADEC default attenuation rate of 4 (assuming that the DF and AF are multiplied) is likely conservative for hydrocarbon compounds with high attenuation rates (such as toluene, ethylbenzene, xylene, and hexane) but may not be conservative for more recalcitrant compounds such as benzene and the chlorinated compounds. The proposed FMD DAF values show a positive or direct correlation with the Modflow values, but appear to be higher than the Modflow values. The differences between the FMD DAF calculation and the Modflow model results is thought to be due to differences in the models such as converging flow, increasing groundwater velocities with downgradient distance, and hydrodynamic dispersion in the Modflow simulations.

6.3 Modflow Simulations of the Effect of Source Area Length on DAF Values

The third set of Modflow simulations illustrates the effect of the source area length on the DAF value by modeling sources with lengths of 105 feet, 300 feet, and 20 feet. The infiltrating precipitation has a dissolved phase benzene concentration of 0.0665 mg/L (66.5 µg/L), which is equal to the benzene MCL multiplied by the ADEC default DAF value of 13.3. The results of the simulations are displayed in Table 10 and in Figures 25, 26 and 27. The top part of Table 10 lists the input parameters for the model and highlights in tan the source length values, which vary in subsequent simulations. The middle part of Table 10 shows the mixing zone depth and DAF calculated from the current VMD DAF equation, and the mixing zone depth and DAF calculated from the proposed alternative FMD DAF equation. The DFs calculated from the results of the Modflow runs are highlighted in blue. The bottom portion of Table 10 presents dissolved concentrations in the shallow portion of the aquifer. Aquifer layers with benzene concentrations exceeding the benzene MCL are highlighted in yellow.

Modflow Simulation DAF1a – Default Source Length. In this Modflow simulation all site conditions match the ADEC default conditions and the benzene biodegradation half-life was set at 231 days (equal to a reaction rate constant of 0.003/day), which is the average value reported by Suarez and Rifai (1999). The model results are shown in Figure 25 and Table 10. The VMD DAF equation calculates a mixing zone depth of 18 feet and a DAF of 13.3 within this depth. The Modflow results indicate a DAF of about 9.0. The proposed new dilution equation with a half-life of 231 days calculates a DAF of 17. In the Modflow results, benzene

concentrations exceed the benzene MCL in about the top 8 feet of the aquifer, and the average concentration within the mixing zone is slightly above the MCL.

Modflow Simulation DAF3a – Long Source Area. In this Modflow simulation the source is 300 feet long while all other site conditions match the ADEC default conditions. The benzene biodegradation half-life was set at 231 days (equal to a reaction rate constant of 0.003/day), which is the average value reported by Suarez and Rifai (1999). The model results are shown in Figure 26 and Table 10. The VMD DAF equation calculates a mixing zone depth of 53 feet and a DAF of 13.4 within this depth. The Modflow results indicate a DAF of about 25 within the VMD DAF mixing zone. The proposed new FMD DAF equation with a half-life of 231 days calculates a DAF of 19 within the fixed depth mixing zone. In the Modflow results benzene concentrations exceed the benzene MCL in only about the top 10 feet of the aquifer, and the average concentration within the VMD DAF mixing zone is below the MCL. These model results indicate that benzene that enters the aquifer at the upgradient end of the source area is largely biodegraded before it reaches the downgradient end of the source area. This biodegradation of the benzene suggests that the aquifer thickness with benzene concentrations exceeding 0.005 mg/L may be relatively small even for large source areas (the VMD DAF equation mixing zone depth calculation overestimates the depth affected by contaminants), and longer source lengths allow higher AFs.

Modflow Simulation DAF4a – Short Source Area. In this Modflow simulation the source is only 20 feet long while all other site conditions match the ADEC default conditions. The benzene biodegradation half-life was set at 231 days (equal to a reaction rate constant of 0.003 per day), which is the average value reported by Suarez and Rifai (1999). The model results are shown in Figure 27 and Table 10. The VMD DAF equation calculates a mixing zone depth of 3.6 feet and a DAF of 13.4 within this depth. The Modflow results indicate a DAF of only about 5 within the ADEC mixing zone depth. The proposed new FMD DAF equation with a half-life of 231 days calculates a DAF of 20 within the fixed mixing depth. In the Modflow results benzene concentrations exceed the benzene MCL in only about the top 3.2 feet of the aquifer, and the average concentration within the VMD DF equation mixing zone is about twice the MCL. These model results and the results from the previous set of model runs indicate that a fixed value AF does not represent first-order biodegradation processes very well.

Conclusions Regarding the Effect of Source Length on the DAF. As shown in the above set of Modflow simulations, the effect of attenuation/biodegradation is relatively complicated compared to the effects of dilution. For example, AFs differ between large sites and small sites. At large sites with a significant travel distance and travel time in the aquifer beneath the source zone, a large fraction of the hydrocarbon mass in the aquifer will tend to biodegrade relative to a small site. Relatively high attenuation factors are likely representative of processes occurring at large source areas such as those at Fort Wainwright, where the depth and concentration of dissolved hydrocarbon is not as great as predicted by the VMD DAF equation because of extensive biodegradation of the hydrocarbon entering the saturated zone near the upgradient end of the site. Because the AF varies with residence time below the source zone, the AF at sites with low groundwater velocities will tend to be higher than the AF at sites with high groundwater velocities. Note that the effect of attenuation will decrease as the thickness of the seasonally saturated source zone increases (but that the current VMD DAF equation does not account for the presence of saturated

source zone soils). These complexities make it difficult to identify a meaningful default AF. (Therefore, use of a first-order rate function to account for biodegradation in the FMD DAF is desirable.) However, to be conservative for small source areas and recalcitrant compounds, the default AF should have a relatively low or conservative value (such as an AF value of 1), and this AF value should only be applied to the dissolved plume exiting the site below the source zone.

Summary and Recommendations

In this technical background document the processes causing dilution and attenuation were described, and two different DAF equations were compared. One DAF equation calculates a mixing zone depth that varies as the source length changes (this VMD DAF equation is currently used by ADEC). The other DAF equation, called the FMD DAF equation, uses a fixed mixing zone depth.

A sensitivity analysis using the VMD DAF equation shows that the mixing zone depth at sites with large sources and deep aquifers can be relatively deep (>50 ft) and that the soil cleanup level calculated with the VMD DAF equation may vary by orders of magnitude when using reasonable/representative input values. The VMD DAF equation does not account for the presence of NAPL in the saturated zone or address the impact of the greater mass of contaminant contributed by longer source zones, and uses a fixed attenuation rate.

The FMD DAF equation: accounts for the presence of a NAPL smear zone, accounts for the greater mass of contaminant contributed by longer source zones, and allows first-order biodegradation. The proposed depth of the fixed mixing zone is 18 feet (or the thickness of the aquifer, whichever is less). This depth was selected to be less than the depth of the screened interval in most drinking water wells; therefore, it yields a conservative DAF value for protection of the migration-to-groundwater route. A sensitivity analysis using the FMD DAF equation shows that the DAF value is most heavily dependent on the thickness of the NAPL source area within the saturated zone. (Greater saturated zone source thicknesses result in lower DAF values.) Increased infiltration rates and source lengths tend to cause lower dilution factors, and increased groundwater velocities tend to cause increased dilution factors. In general, higher biodegradation rate constants (shorter half-lives) cause greater attenuation; however, simultaneously varying site conditions such as source length, groundwater velocity, infiltration rate, and biodegradation rates can produce complex interactions.

Modflow simulations were conducted to help visualize groundwater concentrations below a source zone and to evaluate the impact of source length and biodegradation rates on the DAF. The Modflow simulations show that at sites with long source areas and low biodegradation rates, the VMD DAF equation allows a significant thickness of aquifer to exceed drinking water standards (32 feet in the example). The Modflow simulations also indicate that for sites with significant biodegradation rates, the effect of increasing source lengths will tend to be offset by biodegradation. That is, the dissolved contaminants emanating from the up gradient portions source zone will tend to be significantly biodegraded before reaching the mixing zone at the downgradient edge of the site. Therefore, when biodegradation is significant, longer source areas may not cause dissolved-phase contaminants to be deflected deeper into the saturated zone or be present at higher average concentrations within a mixing zone.

Based on the DAF equation sensitivity analyses, the Modflow modeling, and an understanding of Alaska site conditions, the Alaska Statement of Cooperation Working Group requests ADEC consider the following recommendations:

- Make the use of the VMD DAF more consistent with the regulatory intent as follows:
 - By only using the existing VMD DAF equation for vadose zone sources (and not for sources which extend to the saturated zone)
 - By limiting the mixing zone depth to the default mixing zone depth of 5.5 meters
 - By multiplying the DF by the AF and modifying the default AF to a value of 4 for fuel hydrocarbons (and a value of one for recalcitrant compounds such as chlorinated solvents)
- Develop a new DAF equation that accounts for the presence of NAPL in the saturated zone, has a fixed mixing zone depth, and characterizes biodegradation as a first-order function. An equation meeting these general criteria is presented in this report. Note that the proposed equation yields the same DF as the existing equation for the default site conditions; therefore, the Table B1 and B2 soil screening values need not change (provided that the default site conditions are conservative – if NAPL is present in the saturated zone, the default site conditions do not apply).
- The DAF, phase partitioning, and migration-to-groundwater calculations should be used as a tool to accomplish the following:
 - Understand the phase partitioning and fate and transport processes that occur at contaminated sites
 - Assess the suitability of offsite disposal of contaminated soils. This use of the DAF and phase partitioning equations allows soils to be placed in categories based on whether the soils can be used as offsite fill and whether the fill may be placed in the saturated zone or only in the vadose zone.
- When assessing human health risks for site closeout, measured groundwater concentrations should be used to assess human health risks from the groundwater ingestion route. This approach is consistent with ADEC cumulative risk guidance.
- Where site conditions prohibit or severely limit the ability to conduct groundwater sampling, DAF and migration-to-groundwater calculations may be used as a tool to assess potential human health risk from the groundwater ingestion route. In these circumstances, enough site condition data must be collected to ensure that the DAF and migration-to-groundwater risk calculations are conservative. (Most importantly, the presence or absence of NAPL in the saturated zone must be documented.)
- Sites with good-quality groundwater data and groundwater concentrations meeting risk-based standards (Table C, ambient water quality criteria, or both) should be considered to meet the groundwater criteria for site closure. To achieve closure, the site would also have to meet the cumulative risk criteria and environmental risk criteria. The Alaska Statement of Cooperation Working Group understands that use of a migration to groundwater calculation that includes a default DAF to establish risk-based soil cleanup

levels does not appear to be the best method for determining the need for, or adequacy of, soil cleanup and site closure.

SECTION 8

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Tables

Table 1A Dissolved Phase BTEX Reaction Rates and Half Lives (From Suarez and Rafai, 1999)

Compound		Aerobic Field & Laboratory Studies	Aerobic Field Studies	Anaerobic Field & Laboratory Studies	Anaerobic Field Studies
Benzene	Number of Measurements	26	3	104	45
	Mean Reaction Rate K (day-1)	0.335	0.333	0.008	0.003
	std. Dev.	0.599		0.016	0.006
	Half Life (days)	2	2	87	231
Toluene	Number of Measurements	16	3	106	43
	Mean Reaction Rate K (day-1)	0.262	0.233	0.232	0.237
	std. Dev.	0.384		0.64	0.733
	Half Life (days)	3	3	3	3
Ethylbenzene	Number of Measurements			69	33
	Mean Reaction Rate K (day-1)			0.148	0.218
	std. Dev.			0.735	1.057
	Half Life (days)			5	3
m-Xylene	Number of Measurements	4		73	30
	Mean Reaction Rate K (day-1)	0.163		0.062	0.031
	std. Dev.			0.107	0.061
	Half Life (days)	4		11	22
o-Xylene	Number of Measurements	10	3	70	27
	Mean Reaction Rate K (day-1)	0.086	0.06	0.015	0.019
	std. Dev.	0.116		0.031	0.044
	Half Life (days)	8	12	46	36
p-Xylene	Number of Measurements	3		47	25
	Mean Reaction Rate K (day-1)	0.207		0.037	0.013
	std. Dev.			0.09	0.02
	Half Life (days)	3		19	53

Table 1B Dissolved Phase BTEX Reaction Rates From Alaskan Sites (Geosphere 1997a, 1997b)

Location/ Reference	Reaction Rate & Half Life	Compound			
		Benzene	Toluene	Ethylbenzene	Xylene
Prudhoe Bay	Mean Reaction Rate K (day-1)	0.025	0.019	0.0059	0.016
Geosphere 1997a, 1997b	Half Life (days)	28	36	117	43

Table 2 Migration-to-Groundwater Sensitivity Analysis (using the Method 3 EPA SSL DAF Equation)

source length (m)	aquifer thickness (m)	hydraulic conductivity (m/yr)	hydraulic gradient (i)	attenuation factor (A)	infiltration rate (m)	bulk density (g/cm ³)	foc	moisture content (%)	Benzene Migration to Ground Water Soil Screening Level (mg/kg)	Range of Variability
1	10	876	0.002	4	0.13	1.5	0.001	20	0.019	2.045
5	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
10	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
100	10	876	0.002	4	0.13	1.5	0.001	20	0.013	
200	10	876	0.002	4	0.13	1.5	0.001	20	0.009	
32	1	876	0.002	4	0.13	1.5	0.001	20	0.008	2.403
32	5	876	0.002	4	0.13	1.5	0.001	20	0.017	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	20	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	50	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	100	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	87600	0.002	4	0.13	1.5	0.001	20	0.808	144.019
32	10	8760	0.002	4	0.13	1.5	0.001	20	0.091	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	87.6	0.002	4	0.13	1.5	0.001	20	0.008	
32	10	8.76	0.002	4	0.13	1.5	0.001	20	0.006	
32	10	0.876	0.002	4	0.13	1.5	0.001	20	0.006	
32	10	876	0.0001	4	0.13	1.5	0.001	20	0.007	7.524
32	10	876	0.0005	4	0.13	1.5	0.001	20	0.011	
32	10	876	0.001	4	0.13	1.5	0.001	20	0.014	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	876	0.005	4	0.13	1.5	0.001	20	0.031	
32	10	876	0.01	4	0.13	1.5	0.001	20	0.051	
32	10	876	0.002	1	0.13	1.5	0.001	20	0.005	40.000
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	876	0.002	10	0.13	1.5	0.001	20	0.046	
32	10	876	0.002	20	0.13	1.5	0.001	20	0.093	
32	10	876	0.002	40	0.13	1.5	0.001	20	0.185	
32	10	876	0.002	4	0.0065	1.5	0.001	20	0.170	15.958
32	10	876	0.002	4	0.013	1.5	0.001	20	0.091	
32	10	876	0.002	4	0.065	1.5	0.001	20	0.027	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	876	0.002	4	0.6	1.5	0.001	20	0.011	
32	10	876	0.002	4	0.13	1.4	0.001	20	0.019	1.203
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	876	0.002	4	0.13	1.6	0.001	20	0.018	
32	10	876	0.002	4	0.13	1.8	0.001	20	0.017	
32	10	876	0.002	4	0.13	2	0.001	20	0.016	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	2.898
32	10	876	0.002	4	0.13	1.5	0.002	20	0.022	
32	10	876	0.002	4	0.13	1.5	0.005	20	0.034	
32	10	876	0.002	4	0.13	1.5	0.01	20	0.054	
32	10	876	0.002	4	0.13	1.5	0.001	5	0.011	2.086
32	10	876	0.002	4	0.13	1.5	0.001	10	0.013	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	
32	10	876	0.002	4	0.13	1.5	0.001	28	0.023	
#1 ADEC Default Conditions									Conservatism Factor	
32	10	876	0.002	4	0.13	1.5	0.001	20	0.019	1.00
#2 Outwash gravel, low precip, low moisture in gravel										
32	10	87600	0.002	4	0.013	1.5	0.001	10	5.772	311.61
#3 Clean sand, high gradient, high biodegradation/attenuation rate, low precip, low moisture content										
32	10	8760	0.004	10	0.0325	1.5	0.001	15	1.397	75.42
#4 Silty, dense soil, low gradient,										
32	10	87.6	0.0001	4	0.13	1.8	0.001	20	0.005	0.28

Table 3 Fixed Depth Mixing Zone DAF Sensitivity Analysis-- Source Length, Saturated Source Thickness & Biodegradation Rate

Source Length (m)	Low Water Saturated Source Zone Thickness (m)	High Water Saturated Source Zone Thickness (m)	Seasonal Change in Water Table Elevation (m)	Infiltration Rate (m/yr)	Groundwater Advective Velocity (m/day; =K [*] /n)	Biodegradation Rate (anaerobic half life in Days)	Low Water DF	Low Water AF	Low Water DAF	High Water DF	High Water AF	High Water DAF
2	0	0.0	0.0	0.130	1.1163E-02	1,000,000	37.06	1.00	37.06	37.06	1.00	37.06
5	0	0.0	0.0	0.130	1.1163E-02	1,000,000	14.82	1.00	14.83	14.82	1.00	14.83
10	0	0.0	0.0	0.130	1.1163E-02	1,000,000	7.41	1.00	7.41	7.41	1.00	7.41
20	0	0.0	0.0	0.130	1.1163E-02	1,000,000	3.71	1.00	3.71	3.71	1.00	3.71
32	0	0.0	0.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.32	1.00	2.32
40	0	0.0	0.0	0.130	1.1163E-02	1,000,000	1.85	1.00	1.86	1.85	1.00	1.86
50	0	0.0	0.0	0.130	1.1163E-02	1,000,000	1.48	1.00	1.48	1.48	1.00	1.48
2	0	0.5	0.5	0.130	1.1163E-02	1,000,000	37.06	1.00	37.06	9.25	1.00	9.25
5	0	0.5	0.5	0.130	1.1163E-02	1,000,000	14.82	1.00	14.83	6.89	1.00	6.89
10	0	0.5	0.5	0.130	1.1163E-02	1,000,000	7.41	1.00	7.41	4.83	1.00	4.83
20	0	0.5	0.5	0.130	1.1163E-02	1,000,000	3.71	1.00	3.71	3.02	1.00	3.03
32	0	0.5	0.5	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.09	1.00	2.09
40	0	0.5	0.5	0.130	1.1163E-02	1,000,000	1.85	1.00	1.86	1.73	1.00	1.73
50	0	0.5	0.5	0.130	1.1163E-02	1,000,000	1.48	1.00	1.48	1.43	1.00	1.43
2	0	1.0	1.0	0.130	1.1163E-02	1,000,000	37.06	1.00	37.06	5.66	1.00	5.66
5	0	1.0	1.0	0.130	1.1163E-02	1,000,000	14.82	1.00	14.83	4.74	1.00	4.74
10	0	1.0	1.0	0.130	1.1163E-02	1,000,000	7.41	1.00	7.41	3.73	1.00	3.73
20	0	1.0	1.0	0.130	1.1163E-02	1,000,000	3.71	1.00	3.71	2.62	1.00	2.62
32	0	1.0	1.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.93	1.00	1.93
40	0	1.0	1.0	0.130	1.1163E-02	1,000,000	1.85	1.00	1.86	1.64	1.00	1.64
50	0	1.0	1.0	0.130	1.1163E-02	1,000,000	1.48	1.00	1.48	1.38	1.00	1.38
2	0	2.0	2.0	0.130	1.1163E-02	1,000,000	37.06	1.00	37.06	3.49	1.00	3.49
5	0	2.0	2.0	0.130	1.1163E-02	1,000,000	14.82	1.00	14.83	3.16	1.00	3.16
10	0	2.0	2.0	0.130	1.1163E-02	1,000,000	7.41	1.00	7.41	2.74	1.00	2.74
20	0	2.0	2.0	0.130	1.1163E-02	1,000,000	3.71	1.00	3.71	2.15	1.00	2.15
32	0	2.0	2.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.71	1.00	1.72
40	0	2.0	2.0	0.130	1.1163E-02	1,000,000	1.85	1.00	1.86	1.51	1.00	1.51
50	0	2.0	2.0	0.130	1.1163E-02	1,000,000	1.48	1.00	1.48	1.31	1.00	1.31
2	0	3.0	3.0	0.130	1.1163E-02	1,000,000	37.06	1.00	37.06	2.70	1.00	2.70
5	0	3.0	3.0	0.130	1.1163E-02	1,000,000	14.82	1.00	14.83	2.52	1.00	2.52
10	0	3.0	3.0	0.130	1.1163E-02	1,000,000	7.41	1.00	7.41	2.27	1.00	2.27
20	0	3.0	3.0	0.130	1.1163E-02	1,000,000	3.71	1.00	3.71	1.90	1.00	1.90
32	0	3.0	3.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.58	1.00	1.58
40	0	3.0	3.0	0.130	1.1163E-02	1,000,000	1.85	1.00	1.86	1.42	1.00	1.43
50	0	3.0	3.0	0.130	1.1163E-02	1,000,000	1.48	1.00	1.48	1.27	1.00	1.27

Table 4 Fixed Depth Mixing Zone DAF Sensitivity Analysis-- Source Length, Saturated Source Thickness & Biodegradation Rate

Source Length (m)	Low Water Saturated Source Zone Thickness (m)	High Water Saturated Source Zone Thickness (m)	Seasonal Change in Water Table Elevation (m)	Infiltration Rate (m/yr)	Groundwater Advective Velocity (m/day; =K*i/n)	Biodegradation Rate (anaerobic half life in Days)	Low Water DF	Low Water AF	Low Water DAF	High Water DF	High Water AF	High Water DAF
2	0	0.0	0.0	0.130	1.1163E-02	25	37.06	5.05	187.31	37.06	5.05	187.31
5	0	0.0	0.0	0.130	1.1163E-02	25	14.82	13.23	196.17	14.82	13.23	196.17
10	0	0.0	0.0	0.130	1.1163E-02	25	7.41	31.73	235.22	7.41	31.73	235.22
20	0	0.0	0.0	0.130	1.1163E-02	25	3.71	119.03	441.14	3.71	119.03	441.14
32	0	0.0	0.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	2.32	531.80	1231.84
40	0	0.0	0.0	0.130	1.1163E-02	25	1.85	1436.68	2662.28	1.85	1436.68	2662.28
50	0	0.0	0.0	0.130	1.1163E-02	25	1.48	4974.22	7374.09	1.48	4974.22	7374.09
2	0	0.5	0.5	0.130	1.1163E-02	25	37.06	5.05	187.31	9.25	1.22	11.33
5	0	0.5	0.5	0.130	1.1163E-02	25	14.82	13.23	196.17	6.89	1.65	11.36
10	0	0.5	0.5	0.130	1.1163E-02	25	7.41	31.73	235.22	4.83	2.37	11.46
20	0	0.5	0.5	0.130	1.1163E-02	25	3.71	119.03	441.14	3.02	3.87	11.71
32	0	0.5	0.5	0.130	1.1163E-02	25	2.32	531.80	1231.84	2.09	5.70	11.89
40	0	0.5	0.5	0.130	1.1163E-02	25	1.85	1436.68	2662.28	1.73	6.91	11.95
50	0	0.5	0.5	0.130	1.1163E-02	25	1.48	4974.22	7374.09	1.43	8.41	11.98
2	0	1.0	1.0	0.130	1.1163E-02	25	37.06	5.05	187.31	5.66	1.12	6.31
5	0	1.0	1.0	0.130	1.1163E-02	25	14.82	13.23	196.17	4.74	1.33	6.32
10	0	1.0	1.0	0.130	1.1163E-02	25	7.41	31.73	235.22	3.73	1.70	6.35
20	0	1.0	1.0	0.130	1.1163E-02	25	3.71	119.03	441.14	2.62	2.45	6.42
32	0	1.0	1.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.93	3.36	6.47
40	0	1.0	1.0	0.130	1.1163E-02	25	1.85	1436.68	2662.28	1.64	3.96	6.49
50	0	1.0	1.0	0.130	1.1163E-02	25	1.48	4974.22	7374.09	1.38	4.71	6.50
2	0	2.0	2.0	0.130	1.1163E-02	25	37.06	5.05	187.31	3.49	1.06	3.70
5	0	2.0	2.0	0.130	1.1163E-02	25	14.82	13.23	196.17	3.16	1.17	3.70
10	0	2.0	2.0	0.130	1.1163E-02	25	7.41	31.73	235.22	2.74	1.36	3.71
20	0	2.0	2.0	0.130	1.1163E-02	25	3.71	119.03	441.14	2.15	1.73	3.73
32	0	2.0	2.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.71	2.18	3.74
40	0	2.0	2.0	0.130	1.1163E-02	25	1.85	1436.68	2662.28	1.51	2.48	3.75
50	0	2.0	2.0	0.130	1.1163E-02	25	1.48	4974.22	7374.09	1.31	2.85	3.75
2	0	3.0	3.0	0.130	1.1163E-02	25	37.06	5.05	187.31	2.70	1.04	2.81
5	0	3.0	3.0	0.130	1.1163E-02	25	14.82	13.23	196.17	2.52	1.11	2.81
10	0	3.0	3.0	0.130	1.1163E-02	25	7.41	31.73	235.22	2.27	1.24	2.81
20	0	3.0	3.0	0.130	1.1163E-02	25	3.71	119.03	441.14	1.90	1.49	2.82
32	0	3.0	3.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.58	1.79	2.83
40	0	3.0	3.0	0.130	1.1163E-02	25	1.85	1436.68	2662.28	1.42	1.99	2.83
50	0	3.0	3.0	0.130	1.1163E-02	25	1.48	4974.22	7374.09	1.27	2.24	2.83

Table 5 Fixed Depth Mixing Zone DAF Sensitivity Analysis-- Biodegradation Rate & Saturated Source Thickness

Source Length (m)	Low Water Saturated Source Zone Thickness (m)	High Water Saturated Source Zone Thickness (m)	Seasonal Change in Water Table Elevation (m)	Infiltration Rate (m/yr)	Groundwater Advective Velocity (m/day; =K [*] /n)	Biodegradation Rate (anaerobic half life in Days)	Low Water DF	Low Water AF	Low Water DAF	High Water DF	High Water AF	High Water DAF
32	0	0.0	0.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	2.32	531.80	1231.84
32	0	0.0	0.0	0.130	1.1163E-02	50	2.32	71.40	165.57	2.32	71.40	165.57
32	0	0.0	0.0	0.130	1.1163E-02	100	2.32	23.27	53.96	2.32	23.27	53.96
32	0	0.0	0.0	0.130	1.1163E-02	200	2.32	10.34	23.97	2.32	10.34	23.97
32	0	0.0	0.0	0.130	1.1163E-02	400	2.32	5.05	11.71	2.32	5.05	11.71
32	0	0.0	0.0	0.130	1.1163E-02	1,000	2.32	2.30	5.34	2.32	2.30	5.34
32	0	0.0	0.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.32	1.00	2.32
32	0	0.5	0.5	0.130	1.1163E-02	25	2.32	531.80	1231.84	2.09	5.70	11.89
32	0	0.5	0.5	0.130	1.1163E-02	50	2.32	71.57	165.77	2.09	5.39	11.25
32	0	0.5	0.5	0.130	1.1163E-02	100	2.32	23.30	53.98	2.09	4.78	9.97
32	0	0.5	0.5	0.130	1.1163E-02	200	2.32	10.35	23.97	2.09	3.94	8.23
32	0	0.5	0.5	0.130	1.1163E-02	400	2.32	5.05	11.71	2.09	2.96	6.19
32	0	0.5	0.5	0.130	1.1163E-02	1,000	2.32	2.31	5.34	2.09	1.88	3.92
32	0	0.5	0.5	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.09	1.00	2.09
32	0	1.0	1.0	0.130	1.1163E-02	25	2.32	529.40	1227.67	1.93	3.36	6.47
32	0	1.0	1.0	0.130	1.1163E-02	50	2.32	71.40	165.57	1.93	3.26	6.29
32	0	1.0	1.0	0.130	1.1163E-02	100	2.32	23.27	53.96	1.93	3.06	5.90
32	0	1.0	1.0	0.130	1.1163E-02	200	2.32	10.34	23.97	1.93	2.74	5.29
32	0	1.0	1.0	0.130	1.1163E-02	400	2.32	5.05	11.71	1.93	2.29	4.42
32	0	1.0	1.0	0.130	1.1163E-02	1,000	2.32	2.30	5.34	1.93	1.66	3.20
32	0	1.0	1.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.93	1.00	1.93
32	0	2.0	2.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.71	2.18	3.74
32	0	2.0	2.0	0.130	1.1163E-02	50	2.32	71.57	165.77	1.71	2.15	3.69
32	0	2.0	2.0	0.130	1.1163E-02	100	2.32	23.30	53.98	1.71	2.08	3.57
32	0	2.0	2.0	0.130	1.1163E-02	200	2.32	10.35	23.97	1.71	1.96	3.36
32	0	2.0	2.0	0.130	1.1163E-02	400	2.32	5.05	11.71	1.71	1.77	3.04
32	0	2.0	2.0	0.130	1.1163E-02	1,000	2.32	2.31	5.34	1.71	1.44	2.48
32	0	2.0	2.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.71	1.00	1.72
32	0	3.0	3.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.58	1.79	2.83
32	0	3.0	3.0	0.130	1.1163E-02	50	2.32	71.57	165.77	1.58	1.77	2.80
32	0	3.0	3.0	0.130	1.1163E-02	100	2.32	23.30	53.98	1.58	1.73	2.74
32	0	3.0	3.0	0.130	1.1163E-02	200	2.32	10.35	23.97	1.58	1.66	2.63
32	0	3.0	3.0	0.130	1.1163E-02	400	2.32	5.05	11.71	1.58	1.55	2.45
32	0	3.0	3.0	0.130	1.1163E-02	1,000	2.32	2.31	5.34	1.58	1.33	2.11
32	0	3.0	3.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.58	1.00	1.58

Table 6 Fixed Depth Mixing Zone DAF Sensitivity Analysis-- Infiltration Rate, Saturated Source Thickness & Biodegradation Rate

Source Length (m)	Low Water Saturated Source Zone Thickness (m)	High Water Saturated Source Zone Thickness (m)	Seasonal Change in Water Table Elevation (m)	Infiltration Rate (m/yr)	Groundwater Advective Velocity (m/day; =K [*] /i/n)	Biodegradation Rate (anaerobic half life in Days)	Low Water DF	Low Water AF	Low Water DAF	High Water DF	High Water AF	High Water DAF
32	0	0.0	0.0	0.065	1.1163E-02	1,000,000	4.64	1.00	4.64	4.64	1.00	4.64
32	0	0.0	0.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.32	1.00	2.32
32	0	0.0	0.0	0.260	1.1163E-02	1,000,000	1.16	1.00	1.16	1.16	1.00	1.16
32	0	0.0	0.0	0.520	1.1163E-02	1,000,000	1.00	1.00	1.00	1.00	1.00	1.00
32	0	0.5	0.5	0.065	1.1163E-02	1,000,000	4.63	1.00	4.64	3.56	1.00	3.56
32	0	0.5	0.5	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.09	1.00	2.09
32	0	0.5	0.5	0.260	1.1163E-02	1,000,000	1.16	1.00	1.16	1.14	1.00	1.14
32	0	0.5	0.5	0.520	1.1163E-02	1,000,000	1.00	1.00	1.00	1.00	1.00	1.00
32	0	1.0	1.0	0.065	1.1163E-02	1,000,000	4.64	1.00	4.64	2.97	1.00	2.98
32	0	1.0	1.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.93	1.00	1.93
32	0	1.0	1.0	0.260	1.1163E-02	1,000,000	1.16	1.00	1.16	1.13	1.00	1.13
32	0	1.0	1.0	0.520	1.1163E-02	1,000,000	1.00	1.00	1.00	1.00	1.00	1.00
32	0	2.0	2.0	0.065	1.1163E-02	1,000,000	4.63	1.00	4.64	2.35	1.00	2.35
32	0	2.0	2.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.71	1.00	1.72
32	0	2.0	2.0	0.260	1.1163E-02	1,000,000	1.16	1.00	1.16	1.11	1.00	1.11
32	0	2.0	2.0	0.520	1.1163E-02	1,000,000	1.00	1.00	1.00	1.00	1.00	1.00
32	0	3.0	3.0	0.065	1.1163E-02	1,000,000	4.63	1.00	4.64	2.03	1.00	2.03
32	0	3.0	3.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.58	1.00	1.58
32	0	3.0	3.0	0.260	1.1163E-02	1,000,000	1.16	1.00	1.16	1.10	1.00	1.10
32	0	3.0	3.0	0.520	1.1163E-02	1,000,000	1.00	1.00	1.00	1.00	1.00	1.00
32	0	0.0	0.0	0.065	1.1163E-02	25	4.63	531.80	2463.69	4.63	531.80	2463.69
32	0	0.0	0.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	2.32	531.80	1231.84
32	0	0.0	0.0	0.260	1.1163E-02	25	1.16	531.80	615.92	1.16	531.80	615.92
32	0	0.0	0.0	0.520	1.1163E-02	25	1.00	98.87	98.87	1.00	98.87	98.87
32	0	0.5	0.5	0.065	1.1163E-02	25	4.63	531.80	2463.69	3.56	3.36	11.95
32	0	0.5	0.5	0.130	1.1163E-02	25	2.32	531.80	1231.84	2.09	5.70	11.89
32	0	0.5	0.5	0.260	1.1163E-02	25	1.16	531.80	615.92	1.14	10.31	11.79
32	0	0.5	0.5	0.520	1.1163E-02	25	1.00	98.87	98.87	1.00	10.80	10.80
32	0	1.0	1.0	0.065	1.1163E-02	25	4.63	531.80	2463.69	2.97	2.18	6.49
32	0	1.0	1.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.93	3.36	6.47
32	0	1.0	1.0	0.260	1.1163E-02	25	1.16	531.80	615.92	1.13	5.70	6.44
32	0	1.0	1.0	0.520	1.1163E-02	25	1.00	98.87	98.87	1.00	6.16	6.16
32	0	2.0	2.0	0.065	1.1163E-02	25	4.63	531.80	2463.69	2.35	1.59	3.75
32	0	2.0	2.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.71	2.18	3.74
32	0	2.0	2.0	0.260	1.1163E-02	25	1.16	531.80	615.92	1.11	3.36	3.73
32	0	2.0	2.0	0.520	1.1163E-02	25	1.00	98.87	98.87	1.00	3.65	3.65
32	0	3.0	3.0	0.065	1.1163E-02	25	4.63	531.80	2463.69	2.03	1.39	2.83
32	0	3.0	3.0	0.130	1.1163E-02	25	2.32	531.80	1231.84	1.58	1.79	2.83
32	0	3.0	3.0	0.260	1.1163E-02	25	1.16	531.80	615.92	1.10	2.58	2.82
32	0	3.0	3.0	0.520	1.1163E-02	25	1.00	98.87	98.87	1.00	2.78	2.78

Table 7 Fixed Depth Mixing Zone DAF Sensitivity Analysis-- Groundwater Velocity, Saturated Source Thickness & Biodegradation Rate

Source Length (m)	Low Water Saturated Source Zone Thickness (m)	High Water Saturated Source Zone Thickness (m)	Seasonal Change in Water Table Elevation (m)	Infiltration Rate (m/yr)	Groundwater Advective Velocity (m/day; =K*i/n)	Biodegradation Rate (anaerobic half life in Days)	Low Water DF	Low Water AF	Low Water DAF	High Water DF	High Water AF	High Water DAF
32	0	0.0	0.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.32	1.00	2.32
32	0	0.0	0.0	0.130	1.1163E-01	1,000,000	23.19	1.00	23.19	23.19	1.00	23.19
32	0	0.0	0.0	0.130	1.1163E+00	1,000,000	231.90	1.00	231.90	231.90	1.00	231.90
32	0	0.0	0.0	0.130	1.1163E+01	1,000,000	2318.99	1.00	2318.99	2318.99	1.00	2318.99
32	0	0.5	0.5	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	2.09	1.00	2.09
32	0	0.5	0.5	0.130	1.1163E-01	1,000,000	23.16	1.00	23.17	8.14	1.00	8.14
32	0	0.5	0.5	0.130	1.1163E+00	1,000,000	231.63	1.00	231.64	11.46	1.00	11.46
32	0	0.5	0.5	0.130	1.1163E+01	1,000,000	2316.35	1.00	2316.35	11.94	1.00	11.94
32	0	1.0	1.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.93	1.00	1.93
32	0	1.0	1.0	0.130	1.1163E-01	1,000,000	23.19	1.00	23.19	5.25	1.00	5.25
32	0	1.0	1.0	0.130	1.1163E+00	1,000,000	231.90	1.00	231.90	6.35	1.00	6.35
32	0	1.0	1.0	0.130	1.1163E+01	1,000,000	2318.99	1.00	2318.99	6.48	1.00	6.48
32	0	2.0	2.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.71	1.00	1.72
32	0	2.0	2.0	0.130	1.1163E-01	1,000,000	23.16	1.00	23.17	3.35	1.00	3.35
32	0	2.0	2.0	0.130	1.1163E+00	1,000,000	231.63	1.00	231.64	3.71	1.00	3.71
32	0	2.0	2.0	0.130	1.1163E+01	1,000,000	2316.35	1.00	2316.35	3.75	1.00	3.75
32	0	3.0	3.0	0.130	1.1163E-02	1,000,000	2.32	1.00	2.32	1.58	1.00	1.58
32	0	3.0	3.0	0.130	1.1163E-01	1,000,000	23.16	1.00	23.17	2.63	1.00	2.63
32	0	3.0	3.0	0.130	1.1163E+00	1,000,000	231.63	1.00	231.64	2.81	1.00	2.81
32	0	3.0	3.0	0.130	1.1163E+01	1,000,000	2316.35	1.00	2316.35	2.83	1.00	2.83

Table 8 Modflow Characterization of Dilution Factors for Different Length Source Zones

Modflow Input parameters			default dilution			
			default dilution w/o bio	w/o bio & w/ thick aquifer	long source area w/o bio	short source area w/o bio
scenario general description			DF1	DF 2	DF 3	DF4
file name			DF1	DF 2	DF 3	DF4
aquifer thickness (ft)			32	390	390	390
aquifer thickness (m)			10	118.872	118.872	118.872
K (m/yr)			876	876	876	876
i (ft/ft)			0.002	0.002	0.002	0.002
infiltration (m/yr)			0.13	0.13	0.13	0.13
infiltration (ft/yr)			0.4265	0.4265	0.4265	0.4265
source length (ft)			105	105	300	20
source length (m)			32.004	32.004	91.44	6.096
vertical dispersion coefficient (ft)			0.58799285	0.58799285	5.511744	0.3674496
reaction rate constant k (1/day)			0	0	0	0
Benzene Koc			58.9	58.9	58.9	58.9
foc			0.001	0.001	0.001	0.001
recharge conc (mg/L)			0.0165	0.0165	0.0165	0.0165
Variable Mixing Depth Dilution Factor						
ADEC mixing zone depth (ft)			18.0	18.8	53.4	3.6
ADEC mixing zone depth (m)			5.5	5.7	16.3	1.1
ADEC calculated dilution factor			3.3	3.4	3.4	3.4
dilution factor from Modflow within ADEC mixing zone depth			3.2	3.0	2.7	3.5
Fixed Mixing Depth Dilution Factor						
Fixed mixing zone depth (ft)			18.0	18.0	18.0	18.0
Fixed mixing zone depth (m)			5.5	5.5	5.5	5.5
18 ft Fixed Mixing Zone dilution factor			3.3	3.3	1.0	13.2
dilution factor from Modflow within 18 ft fixed mixing zone depth			3.2	3.0	1.5	17.4
Modflow Simulation Results						
thickness of aquifer exceeding MCL (ft)			~9	~9	~32	~2.2
model layer	layer thickness (ft)	cumulative depth below water table (ft)	Dissolved Benzene Concentration (mg/L)			
1	0.2	0.2	0.00111296	0.01144868	0.00885341	0.00724346
2	1	1.2	0.0124929	0.0131105	0.00973224	0.00680688
3	1	2.2	0.0131773	0.0135394	0.0103804	0.00442938
4	1	3.2	0.0129665	0.0130046	0.0106789	0.00239261
5	1	4.2	0.0121228	0.0119055	0.0108312	0.00116083
6	1	5.2	0.0106528	0.0104996	0.010917	0.000537977
7	1	6.2	0.00887937	0.0089704	0.0109704	0.000247321
8	1	7.2	0.00710902	0.00743308	0.0110078	0.000114787
9	1	8.2	0.00549214	0.00596184	0.0110388	5.39854E-05
10	1	9.2	0.00407469	0.00461486	0.0110711	2.56849E-05
11	1	10.2	0.00288315	0.00344272	0.0111128	1.23747E-05
12	1	11.2	0.00194481	0.00248171	0.0111737	6.10606E-06
13	1	12.2	0.00126887	0.00174668	0.0112645	3.16949E-06
14	2	14.2	0.000580043	0.000930087	0.0114408	8.29039E-07
15	2	16.2	0.000176591	0.000354225	0.0116023	3.403E-08
16	2	18.2	3.81E-05	0.000105064	0.0115664	4.33491E-08
17	2	20.2			0.0111841	
18	5	25.2			0.00975402	
19	5	30.2			0.00629138	
20	2.7	32.9			0.00396736	
21	7.3	40.2			0.00175236	
22	12.3	52.5			0.000109884	

Table 9 Modflow Characterization of Dilution Attenuation Factors-- Impact of Biodegradation Rate on the DAF

Modflow Input parameters						
scenario general description			dilution w average bio	dilution w high bio (2x)	dilution w high bio (4x)	dilution w slow bio (1/2x)
file name			DAF1a	DAF1b	DAF1c	DAF1d
aquifer thickness (ft)			32	32	32	32
aquifer thickness (m)			10	10	10	10
K (m/yr)			876	876	876	876
i (ft/ft)			0.002	0.002	0.002	0.002
infiltration (m/yr)			0.13	0.13	0.13	0.13
infiltration (ft/yr)			0.4265	0.4265	0.4265	0.4265
source length (ft)			105	105	105	105
source length (m)			32.004	32.004	32.004	32.004
vertical dispersion coefficient (ft)			0.588	0.588	0.588	0.588
reaction rate constant k (1/day)			0.003	0.006	0.012	0.0015
half life (days)			231	115	58	462
Benzene Koc			58.9	58.9	58.9	58.9
foc			0.001	0.001	0.001	0.001
recharge conc (mg/L)			0.0665	0.0665	0.0665	0.0665
Variable Mixing Depth Dilution Factor						
ADEC mixing zone depth (ft)			18.0	18.0	18.0	18.0
ADEC mixing zone depth (m)			5.5	5.5	5.5	5.5
ADEC calculated dilution factor			3.3	3.3	3.3	3.3
ADEC calculated dilution-attenuation factor			13.3	13.3	13.3	13.3
DAF from Modflow within ADEC mixing zone			9.3	19.1	41.2	6.2
Fixed Mixing Depth Dilution Factor						
Fixed mixing zone depth (ft)			18.0	18.0	18.0	18.0
Fixed mixing zone depth (m)			5.5	5.5	5.5	5.5
18 ft Fixed Mixing Zone dilution-attenuation factor			17.0	30.0	53.0	9.2
DAF from Modflow within 18 ft fixed mixing zone			9.3	19.1	41.2	6.2
Modflow Simulation Results						
thickness of aquifer exceeding MCL (ft)			~7.5	~5	~4	~9.5
model layer	layer thickness (ft)	cumulative depth below water table (ft)	Dissolved Benzene Concentration (mg/L)			
1	0.2	0.2	0.0292186	0.0230812	0.017322	0.0347724
2	1	1.2	0.0290385	0.020816	0.0133548	0.0365888
3	1	2.2	0.02948366	0.0153111	0.00782503	0.0343489
4	1	3.2	0.019834	0.0103517	0.00409182	0.0302414
5	1	4.2	0.0150832	0.00665997	0.00201635	0.0253519
6	1	5.2	0.0109219	0.00409948	0.000949122	0.0201215
7	1	6.2	0.0075741	0.00243635	0.000434203	0.0152272
8	1	7.2	0.0050911	0.00141463	0.000196558	0.0111223
9	1	8.2	0.003323317	0.000802721	8.82284E-05	0.00786251
10	1	9.2	0.00208624	0.000439653	3.86217E-05	0.00533888
11	1	10.2	0.00124415	0.000228599	1.60827E-05	0.00344846
12	1	11.2	0.000702142	0.000111918	6.25931E-06	0.00211487
13	1	12.2	0.00384318	0.000053259	2.36871E-06	0.00125626
14	2	14.2	0.000123753	1.26643E-05	3.26192E-07	0.000477715
15	2	16.2	0.000018997	9.93477E-07	6.8E-09	0.000105009
16	2	18.2	7.94E-07	0.00E+00	0.00E+00	1.15E-05
17	2	20.2		0	0	1.16055E-08

Table 10 Modflow Characterization of Dilution- Attenuation Factors for Variable Source Lengths

Modflow Input parameters				default source	long source,	short source,	
scenario general description		length, dilution w	average bio	dilution w average	bio	dilution w average	bio
file name		DAF1a		DAF3a		DAF4a	
aquifer thickness (ft)		32		390		390	
aquifer thickness (m)		10		118.872		118.872	
K (m/yr)		876		876		876	
i (ft/ft)		0.002		0.002		0.002	
infiltration (m/yr)		0.13		0.13		0.13	
infiltration (ft/yr)		0.4265		0.4265		0.4265	
source length (ft)		105		300		20	
source length (m)		32.004		91.44		6.096	
vertical dispersion coefficient (ft)		0.58799285		5.511744		0.3674496	
reaction rate constant k (1/day)		0.003		0.003		0.003	
half life (days)		231		231		231	
Benzene Koc		58.9		58.9		58.9	
foc		0.001		0.001		0.001	
recharge conc (mg/L)		0.0665		0.0665		0.0665	
Variable Mixing Depth Dilution Factor							
ADEC mixing zone depth (ft)		18.0		53.4		3.6	
ADEC mixing zone depth (m)		5.5		16.3		1.1	
ADEC calculated dilution factor		3.3		3.4		3.4	
ADEC calculated DAF		13.3		13.4		13.4	
DAF from Modflow within ADEC mixing zone depth		9.0		25.4		5.1	
Fixed Mixing Depth Dilution Factor							
Fixed mixing zone depth (ft)		18.0		18.0		18.0	
Fixed mixing zone depth (m)		5.5		5.5		5.5	
18 ft Fixed Mixing Zone dilution factor		2.3		1.0		11.0	
18 ft Fixed Mixing Zone DAF		17.0		19.0		20.0	
DAF from Modflow within 18 ft fixed mixing zone depth		9.0		9.1		27.0	
Modflow Simulation Results							
thickness of aquifer exceeding MCL (ft)				7.5	10.0	3.5	
model layer	layer thickness (ft)	cumulative depth below water table (ft)	Dissolved Benzene Concentration (mg/L)	Dissolved Benzene Concentration (mg/L)	Dissolved Benzene Concentration (mg/L)		
1	0.2	0.2	0.0292186	0.0186614	0.023539		
2	1	1.2	0.0290385	0.0193869	0.0204188		
3	1	2.2	0.02948366	0.0178452	0.0115988		
4	1	3.2	0.019834	0.0155693	0.00517121		
5	1	4.2	0.0150832	0.0132799	0.001193779		
6	1	5.2	0.0109219	0.0112083	0.000639633		
7	1	6.2	0.0075741	0.00940807	0.000191789		
8	1	7.2	0.0050911	0.00787265	5.30784E-05		
9	1	8.2	0.003323317	0.00657587	1.35238E-05		
10	1	9.2	0.00208624	0.005488	3.06812E-06		
11	1	10.2	0.00124415	0.00458156	5.73048E-07		
12	1	11.2	0.000702142	0.00383256	7.8891E-08		
13	1	12.2	0.00384318	0.00322094	6.2E-09		
14	2	14.2	0.000123753	0.00246905	0		
15	2	16.2	0.000018997	0.00175094	0		
16	2	18.2	7.94E-07	0.00123826	0		
17	2	20.2		0.00087332			
18	5	25.2		0.000409335			
19	5	30.2		0.000110368			
20	2.7	32.9		3.66909E-05			
21	7.3	40.2		3.14969E-06			
22	12.3	52.5		0			

Figures

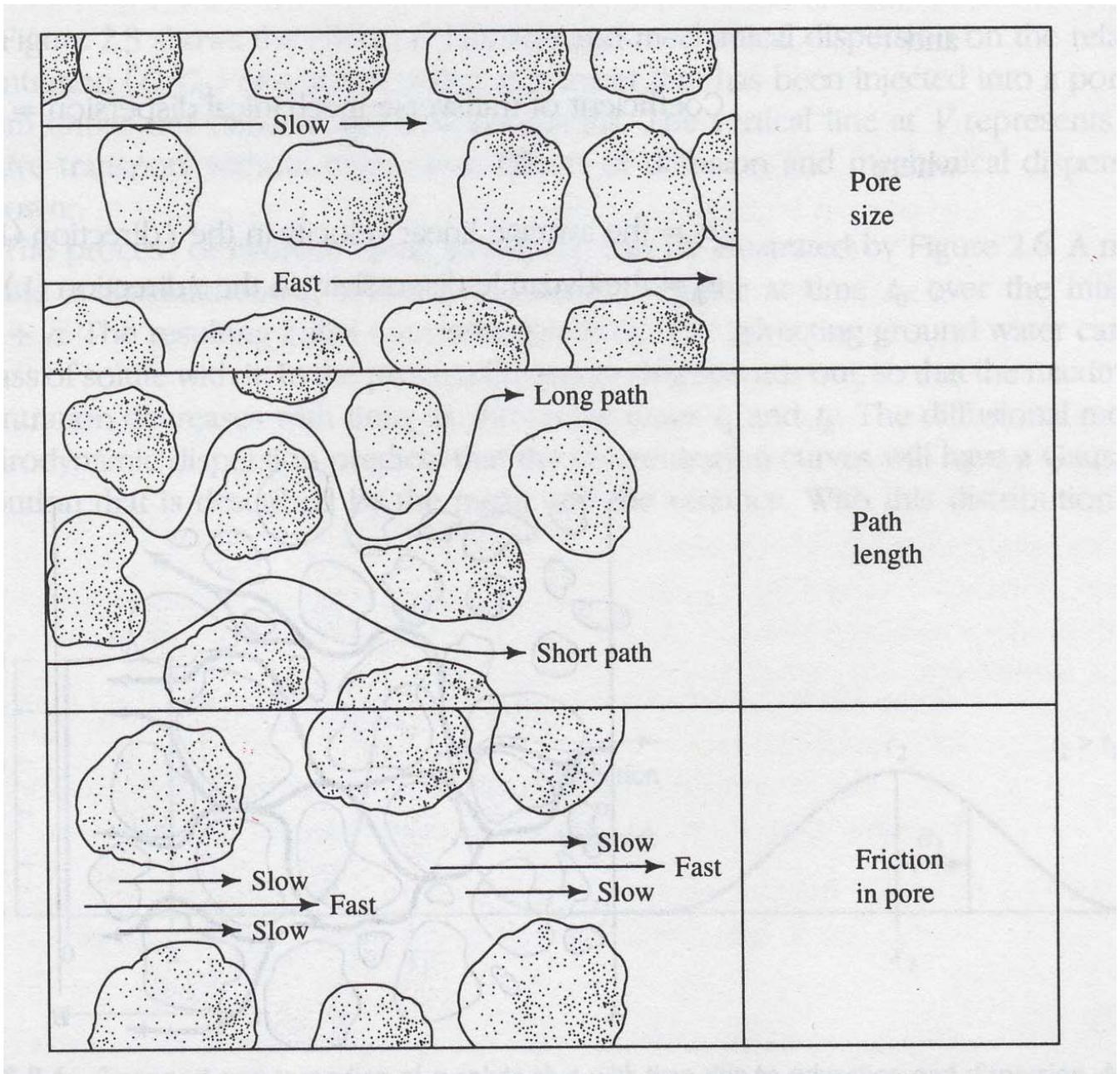


Figure 1 Flow Paths Contributing to Hydrodynamic Dispersion

Flow Path of Infiltrating Precipitation and Mixing Zone Depth Due to Downward Velocity of Infiltrating Precipitation. (No Dispersion)

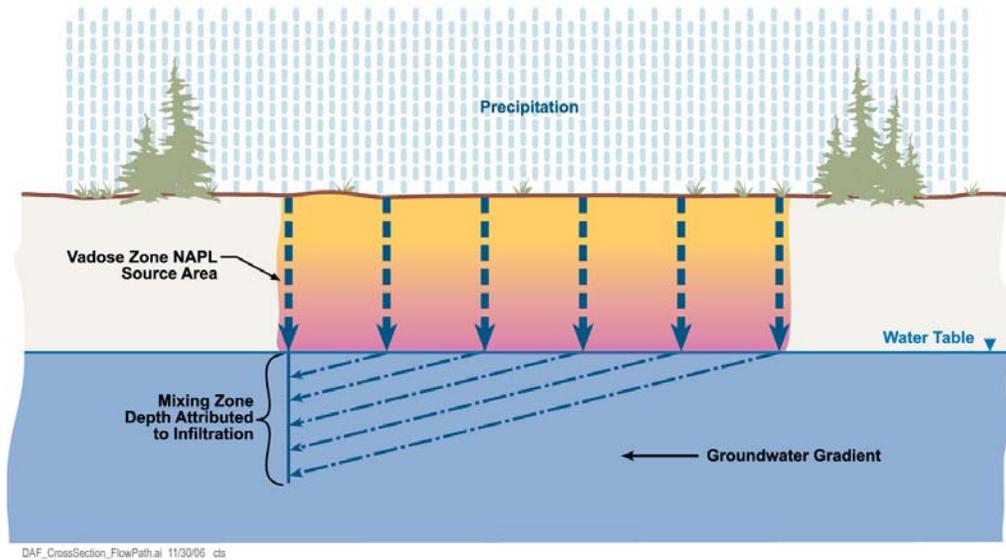


Figure 2 Current EPA & ADEC Dilution Model -- Mixing Zone Depth Due to Downward Velocity of Infiltrating Precipitation

Depth of Hydrocarbon Migration Due to Infiltration and Dispersion

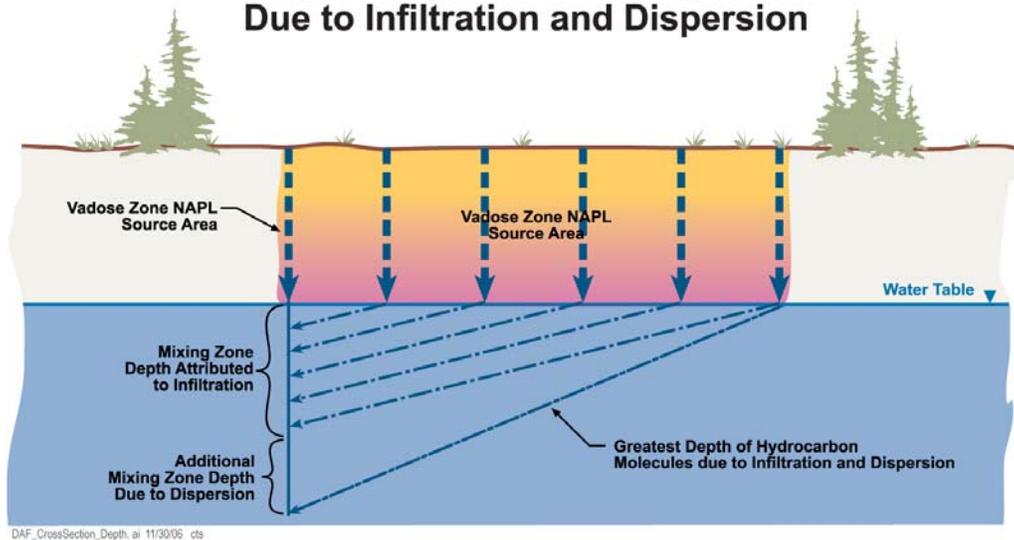


Figure 3 Current EPA & ADEC Dilution Model-- Mixing Zone Depth Due to Downward Velocity of Infiltrating Precipitation + Hydrodynamic Dispersion

Figure 4 Mixing Zone Thickness as Function of Source Length and Aquifer Thickness as Calculated by the EPA SSL Approach

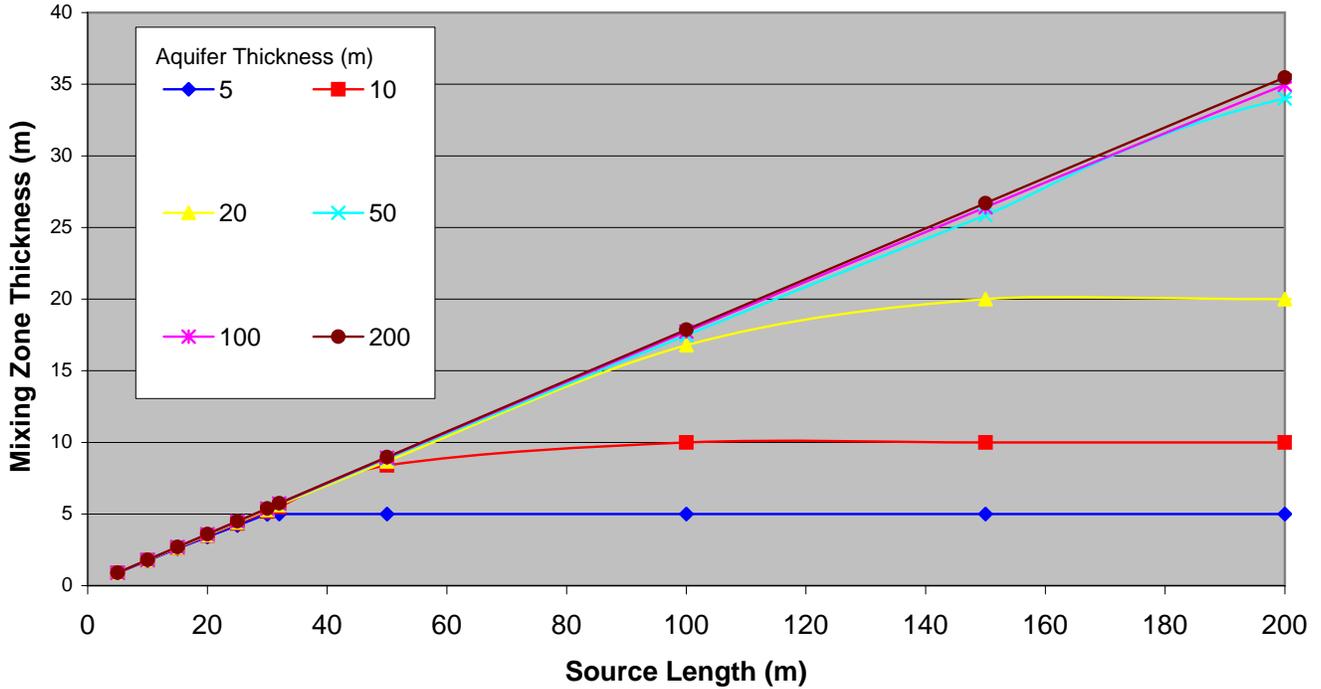


Figure 5 Change in Dilution Factor as a Function of Mixing Zone Depth and Aquifer Thickness as Calculated by the EPA SSL Approach

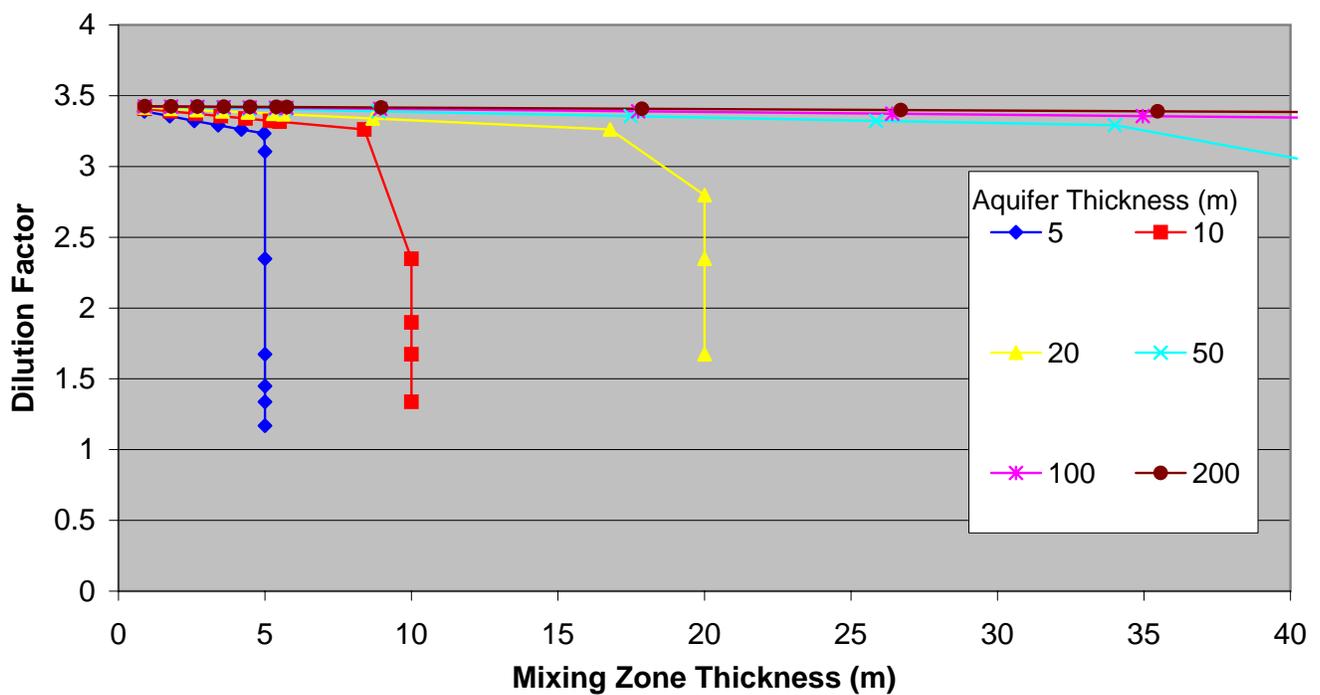


Figure 6 Dilution Factor as a Function of Aquifer Thickness and Source Length as Calculated by the EPA SSL Approach

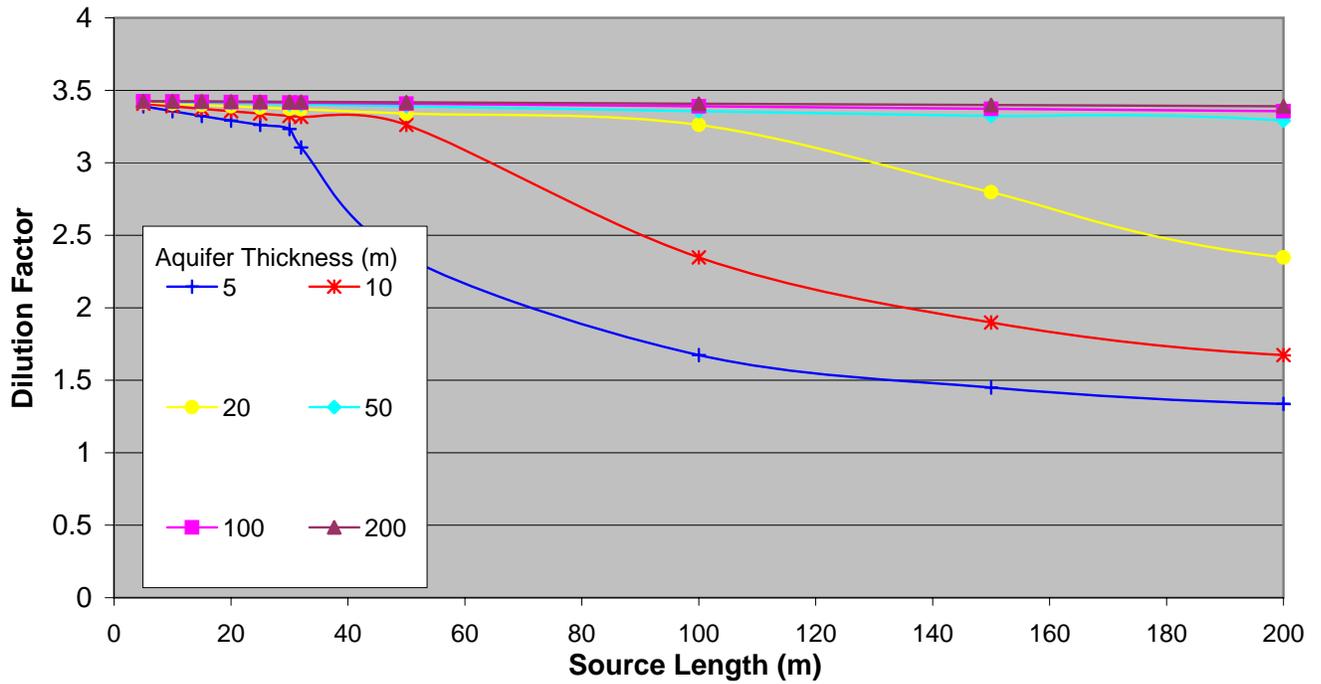


Figure 7 Change in Migration to Groundwater Soil Cleanup Level as a Function of Hydraulic Conductivity

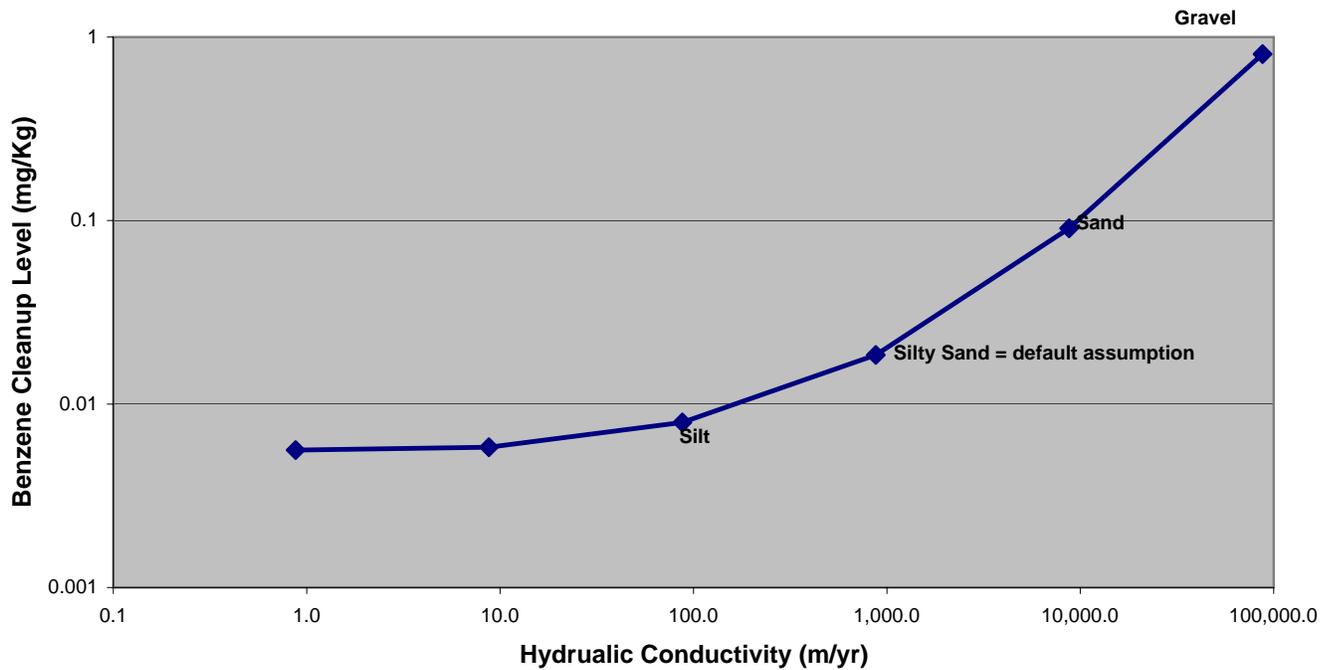


Figure 8 Change in Migration to Groundwater Soil Cleanup Level as a Function of Infiltration

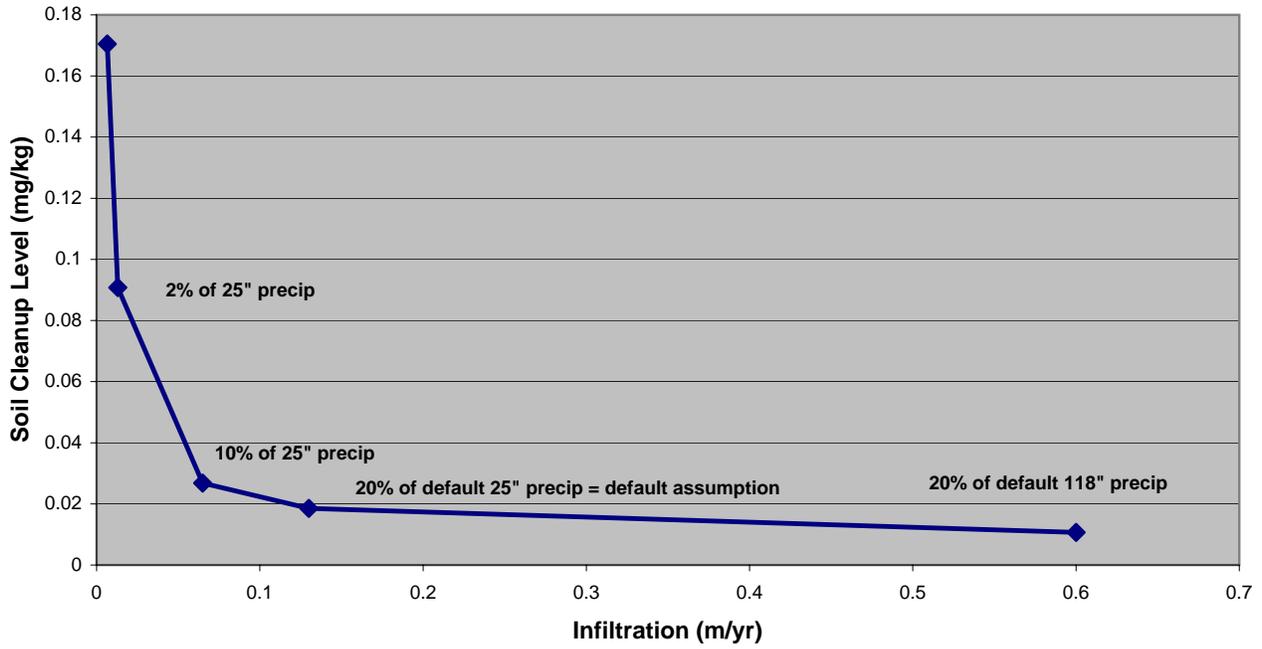


Figure 9 Change in Migration to Groundwater Soil Cleanup Level as a Function of the Fraction of Organic Carbon

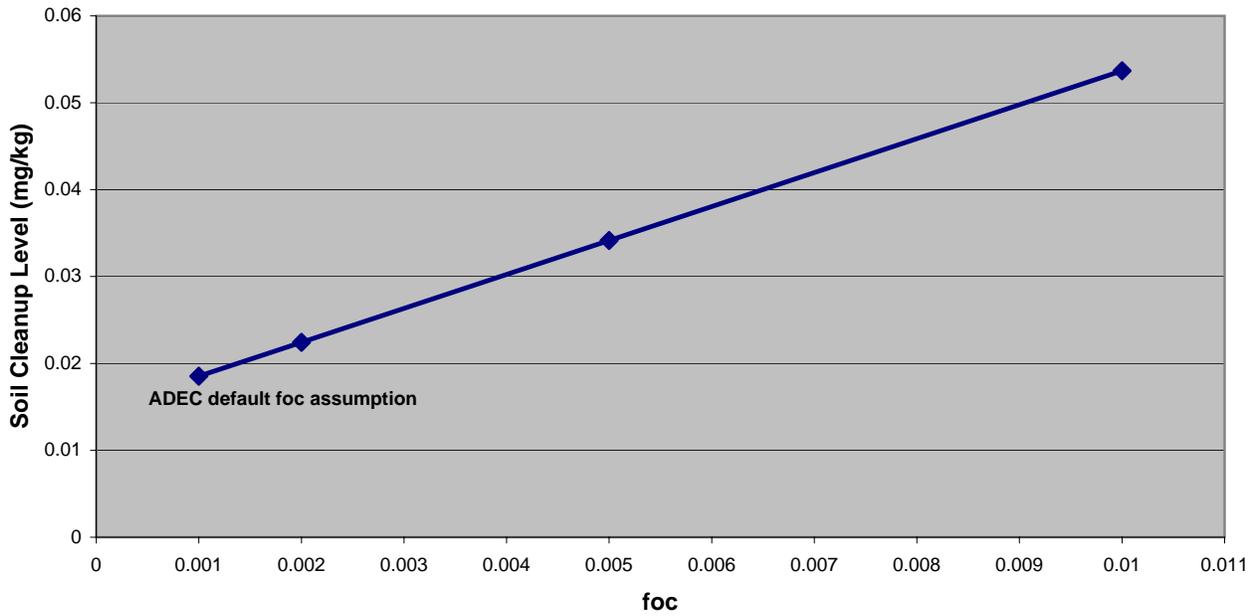


Figure 10 Change in Migration to Groundwater Soil Cleanup Level as a Function of the Soil Moisture Content

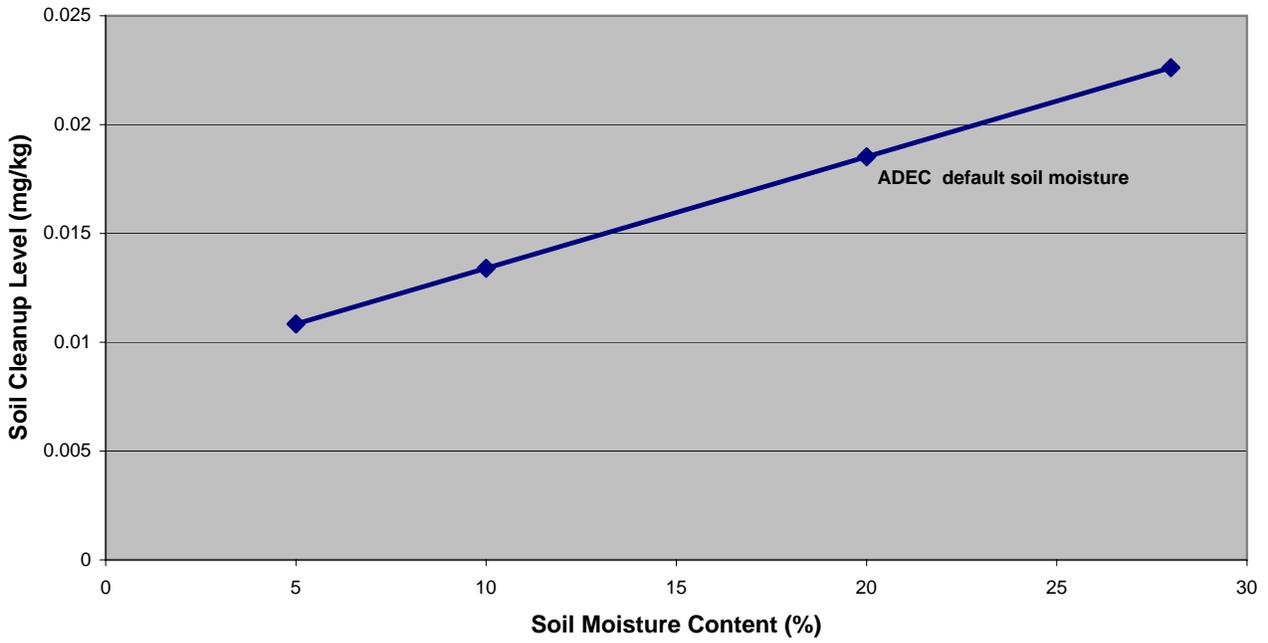
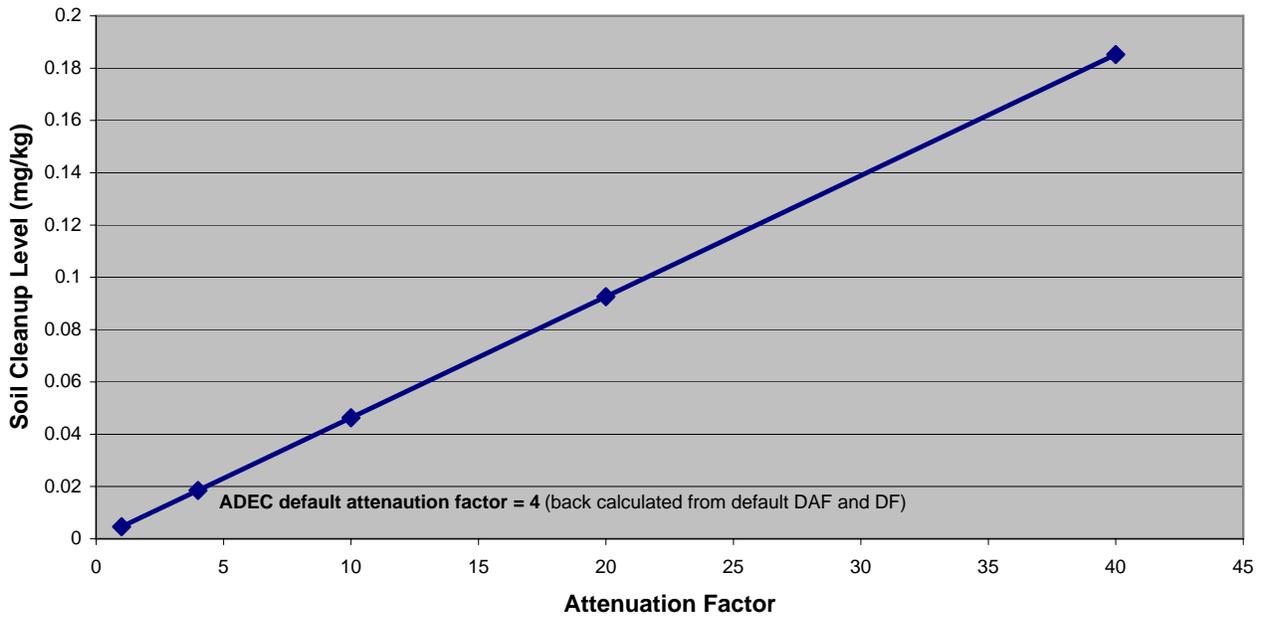


Figure 11 Change in Migration to Groundwater Soil Cleanup Level as a Function of the Attenuation Factor



Proposed Dilution Factor Conceptual Site Conditions

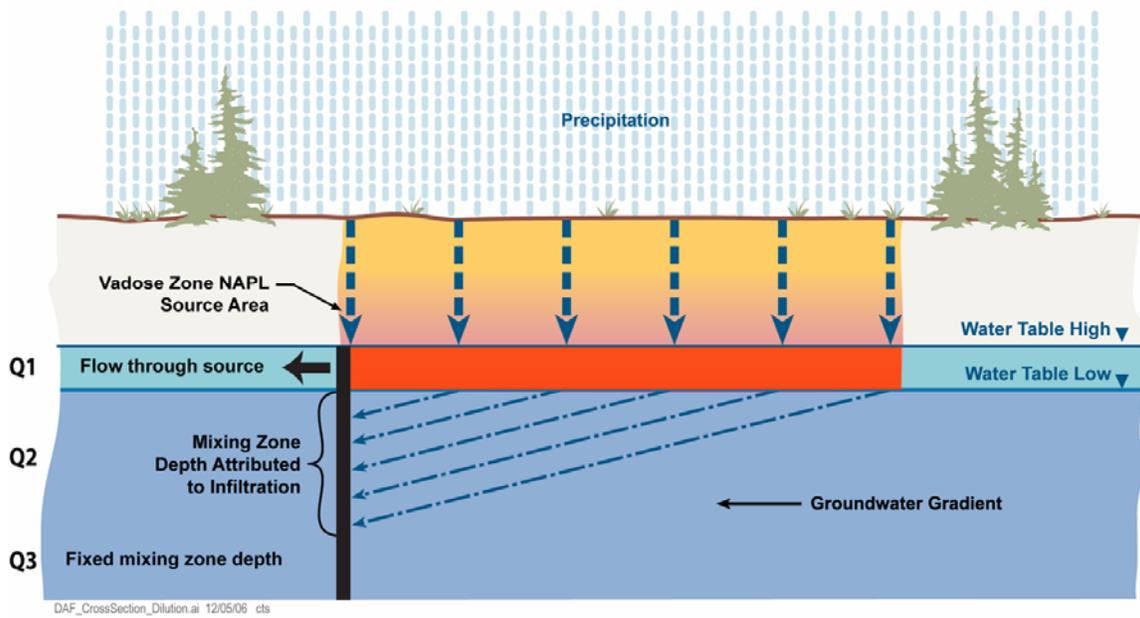


Figure 12 Proposed Dilution Attenuation Factor Conceptual Site Conditions

Figure 13A DAF as a Function of Source Length and Saturated Source Thickness for a Fixed Depth Mixing Zone (Half Life 1,000,000 days)

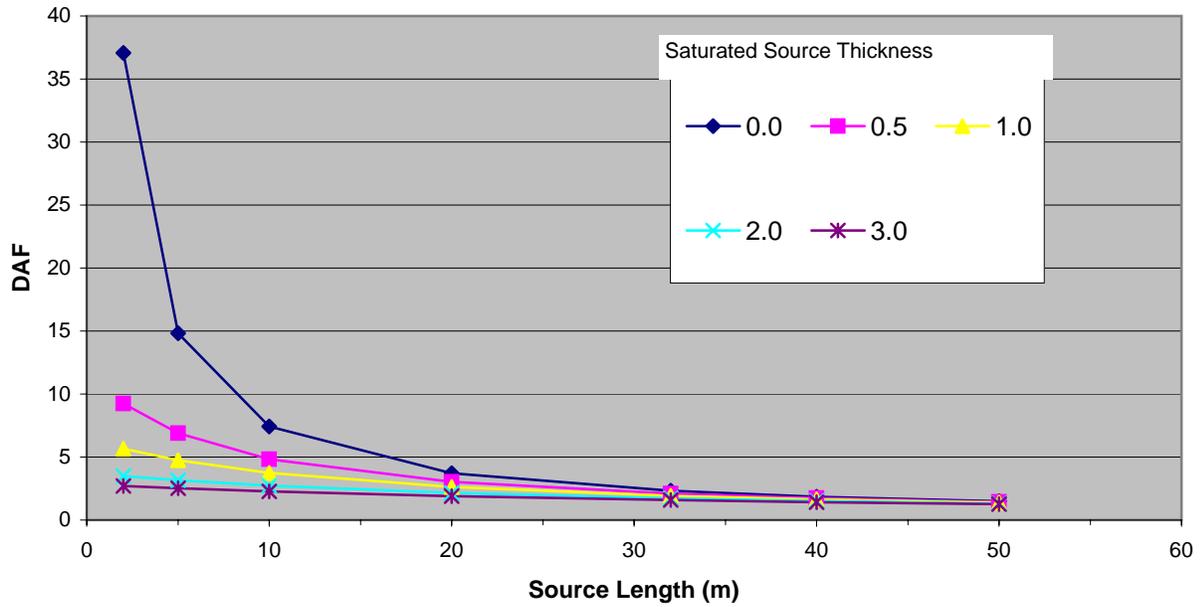


Figure 13B DAF as a Function of Source Length and Saturated Source Thickness for a Fixed Depth Mixing Zone (Half Life 25 days)

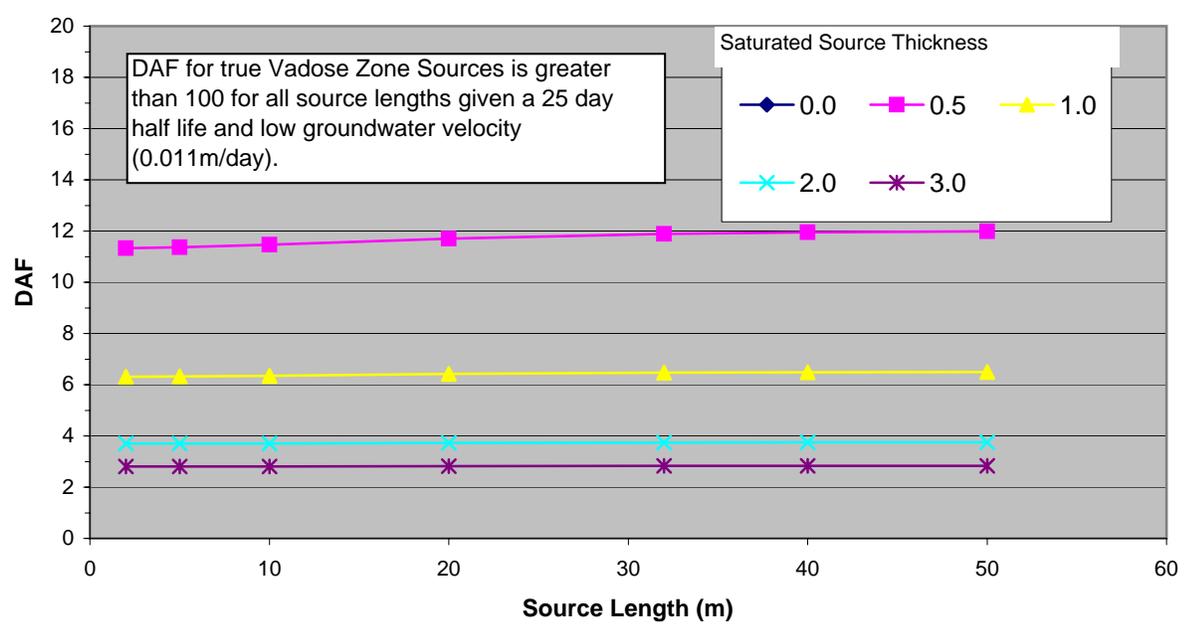


Figure 14 DAF as a Function of Biodegradation Half Life and Saturated Source Thickness for a Fixed Depth Mixing Zone (Source Length 32 m)

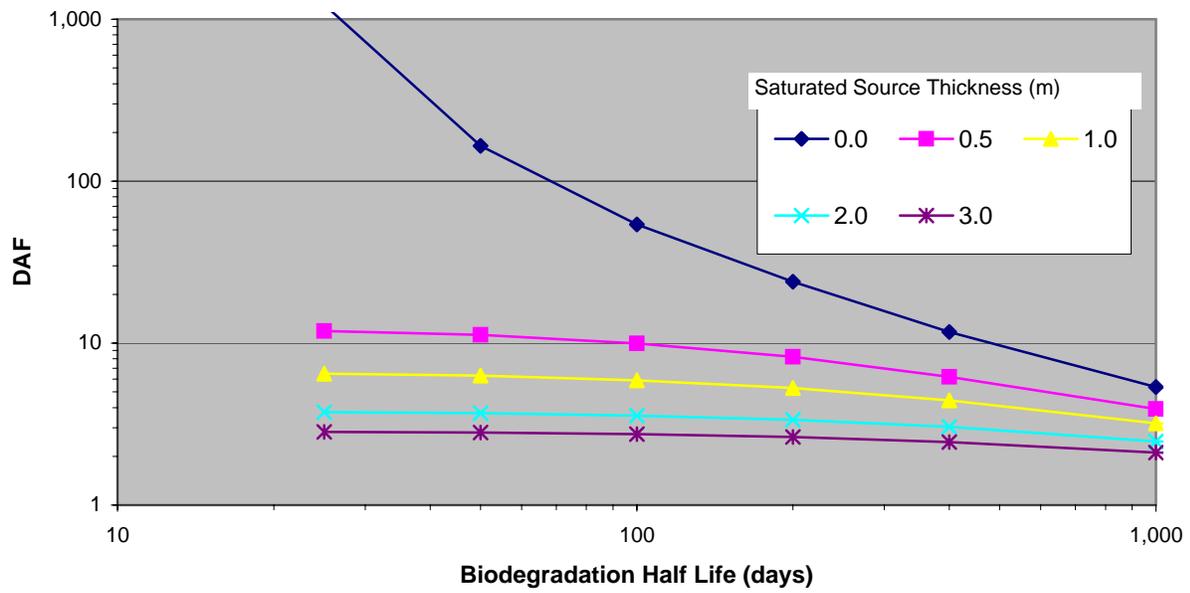


Figure 15A DAF as a Function of Infiltration Rate and Source Thickness for a Fixed Depth Mixing Zone (Half Life 1,000,000 days)

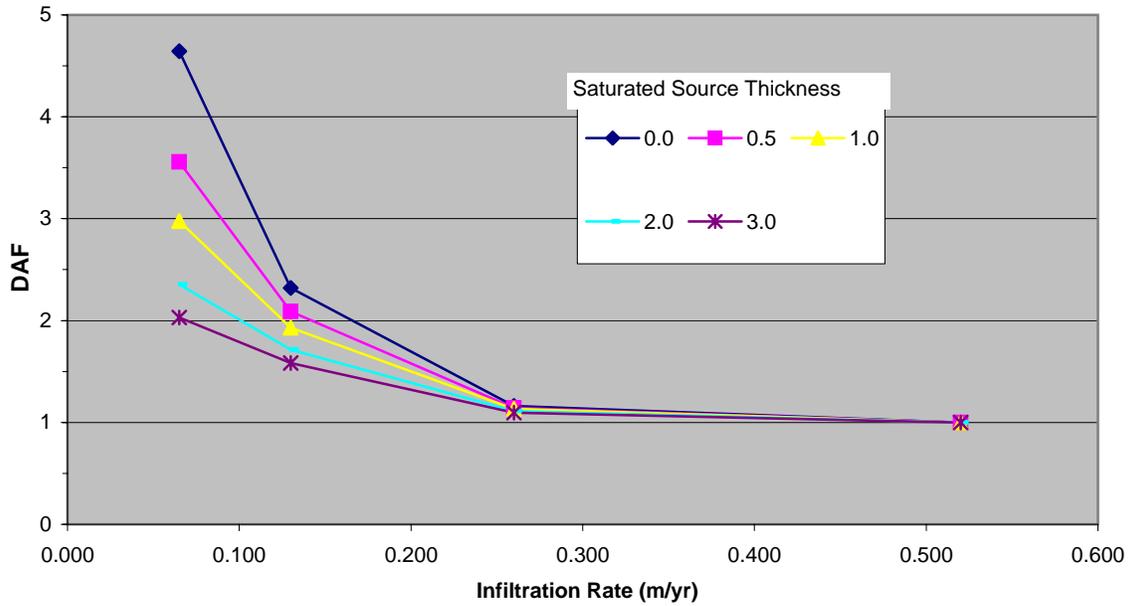


Figure 15B DAF as a Function of Infiltration Rate and Source Thickness for a Fixed Depth Mixing Zone (Half Life 25 days)

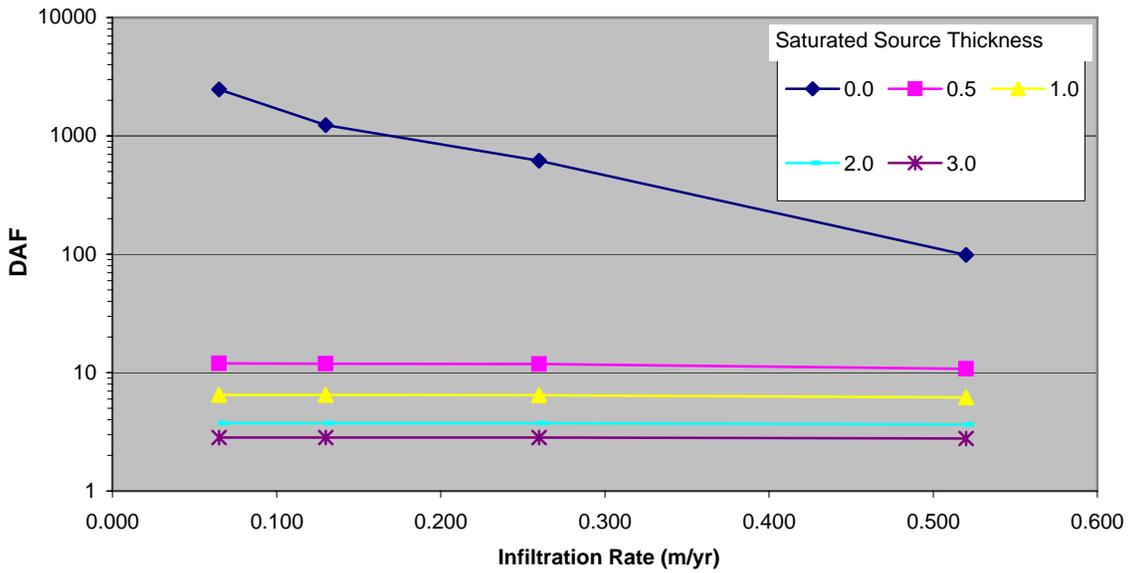


Figure 16A DAF as a Function of Groundwater Velocity and Saturated Source Thickness for a Fixed Depth Mixing Zone (Half Life 1,000,000 days)

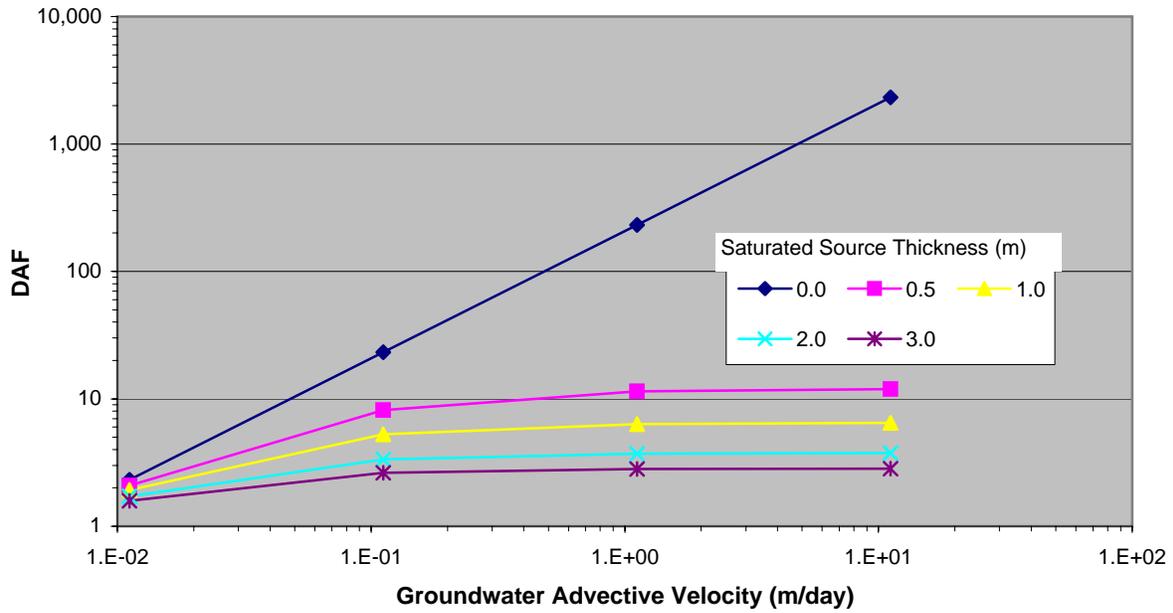
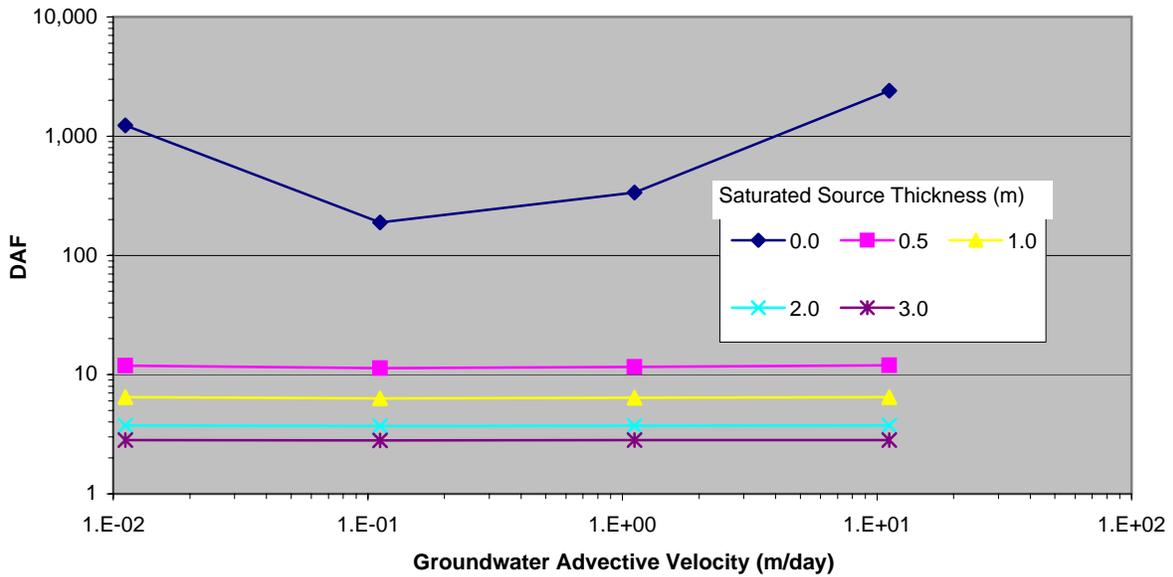


Figure 16B DAF as a Function of Groundwater Velocity and Saturated Source Thickness for a Fixed Depth Mixing Zone (Half Life 25 days)



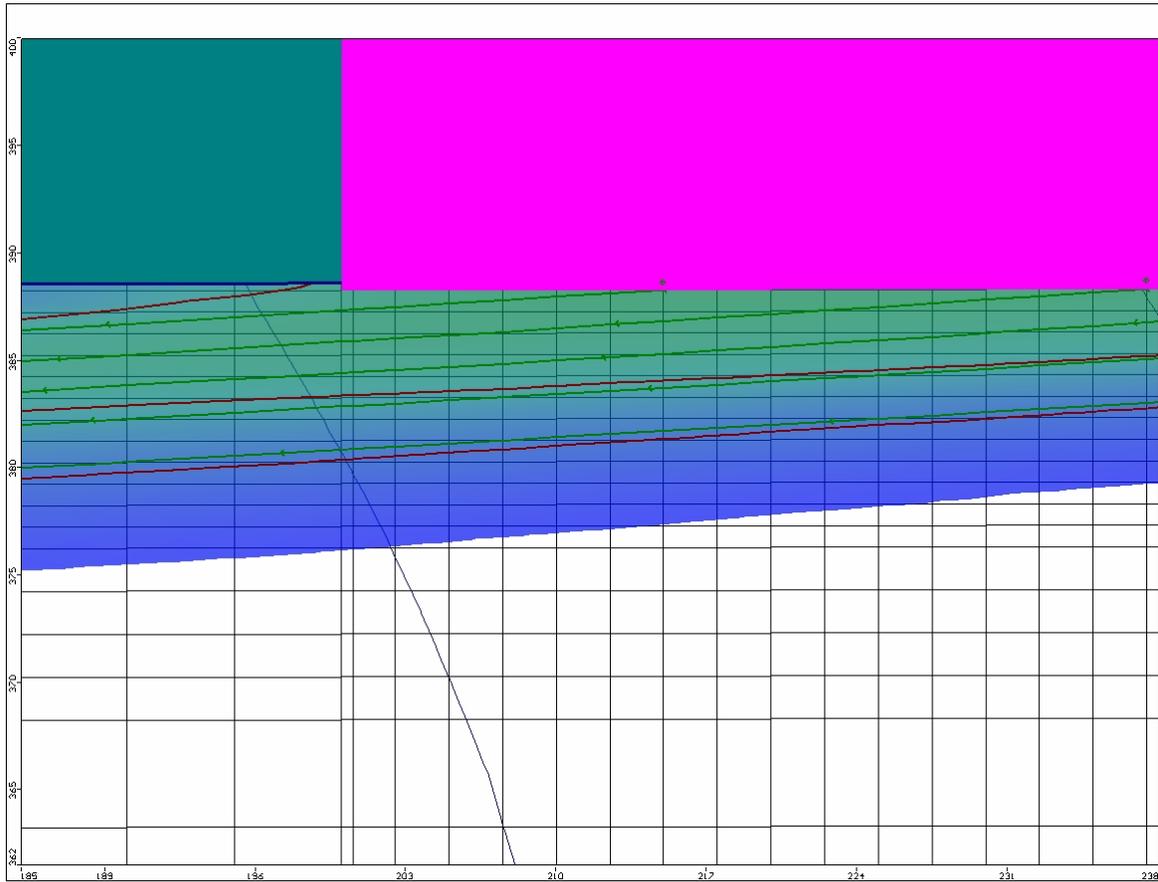


Figure 17 Dissolved Phase Plume Simulated by Modflow (DF1)

Source concentration 16.5 ug/L, 5 ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions.

Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

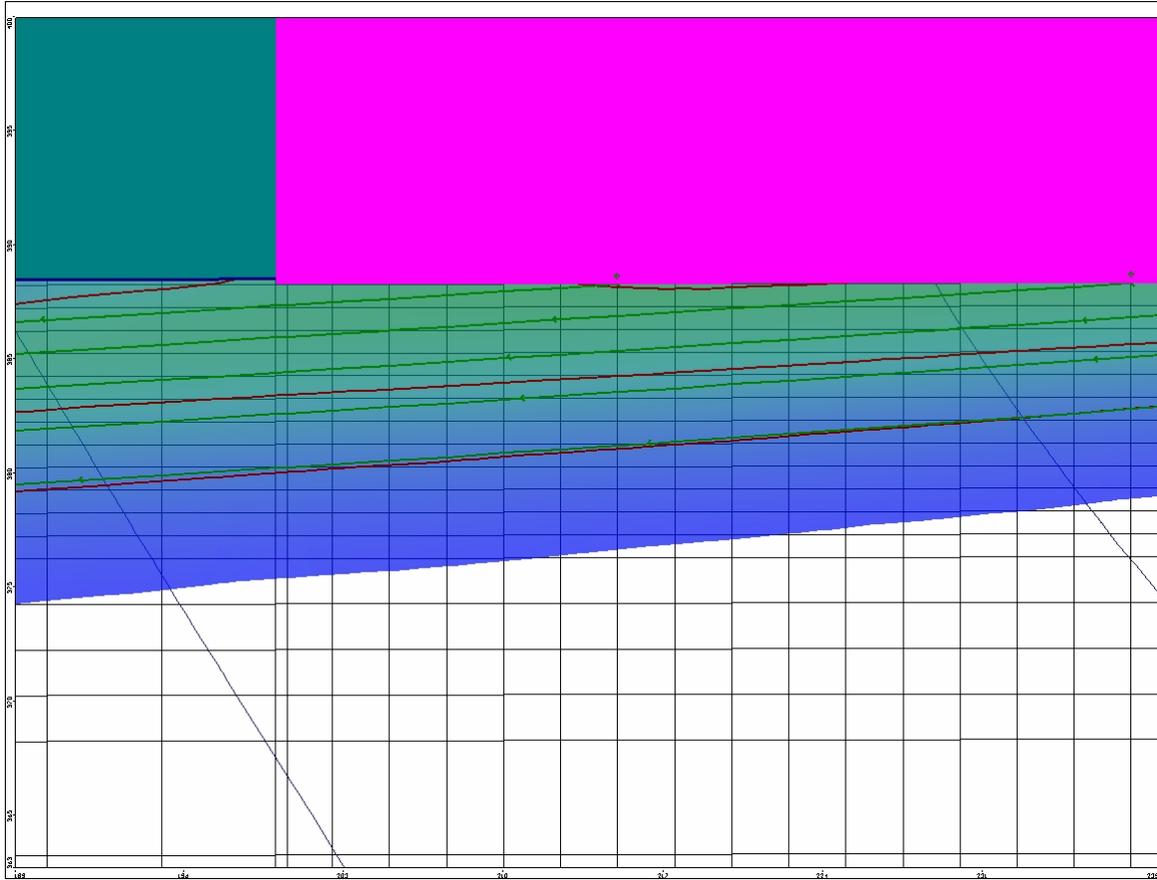


Figure 18 Dissolved Phase Plume simulated by Modflow (DF2)

Source concentration 16.5 ug/L, 5 ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions except for deep aquifer. Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

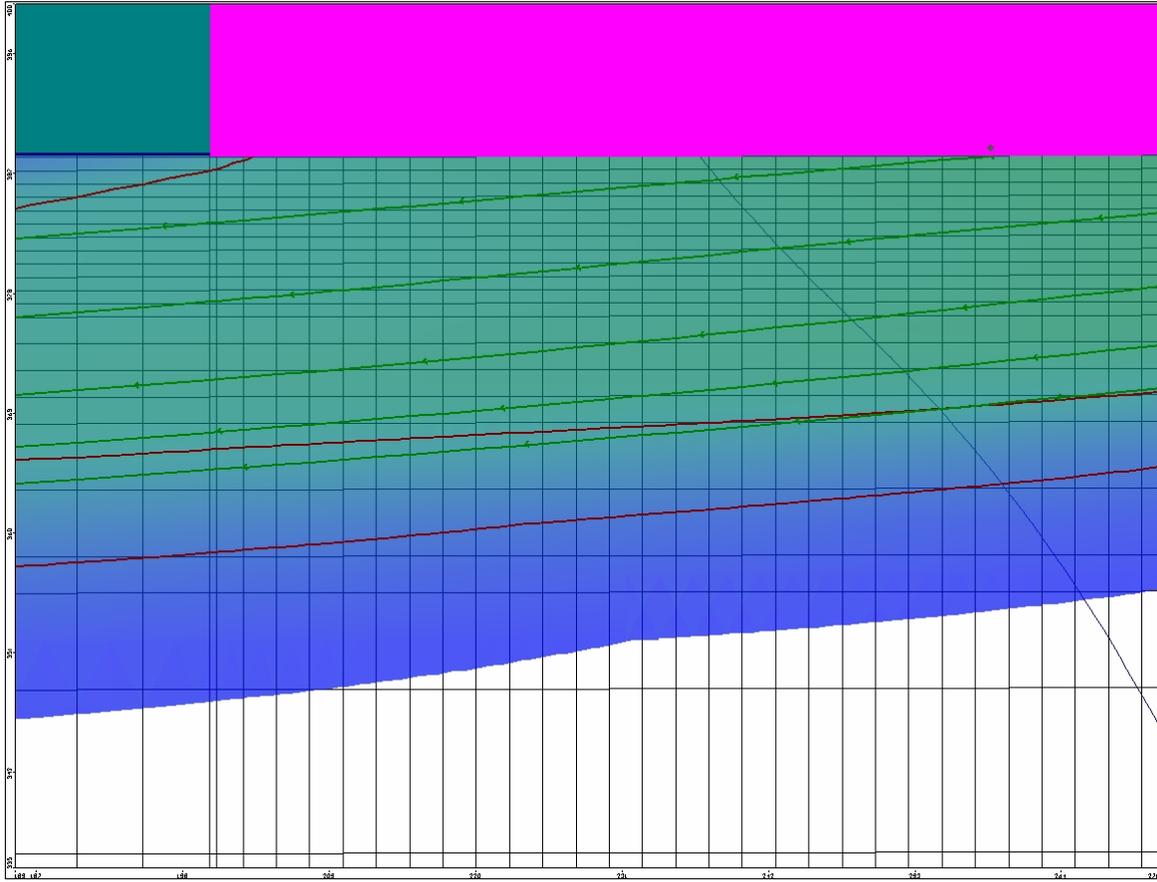


Figure 19 Dissolved Phase Plume simulated by Modflow (DF3)

Source concentration 16.5 ug/L, 5 ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 91 meter source, default site conditions except for deep aquifer. Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

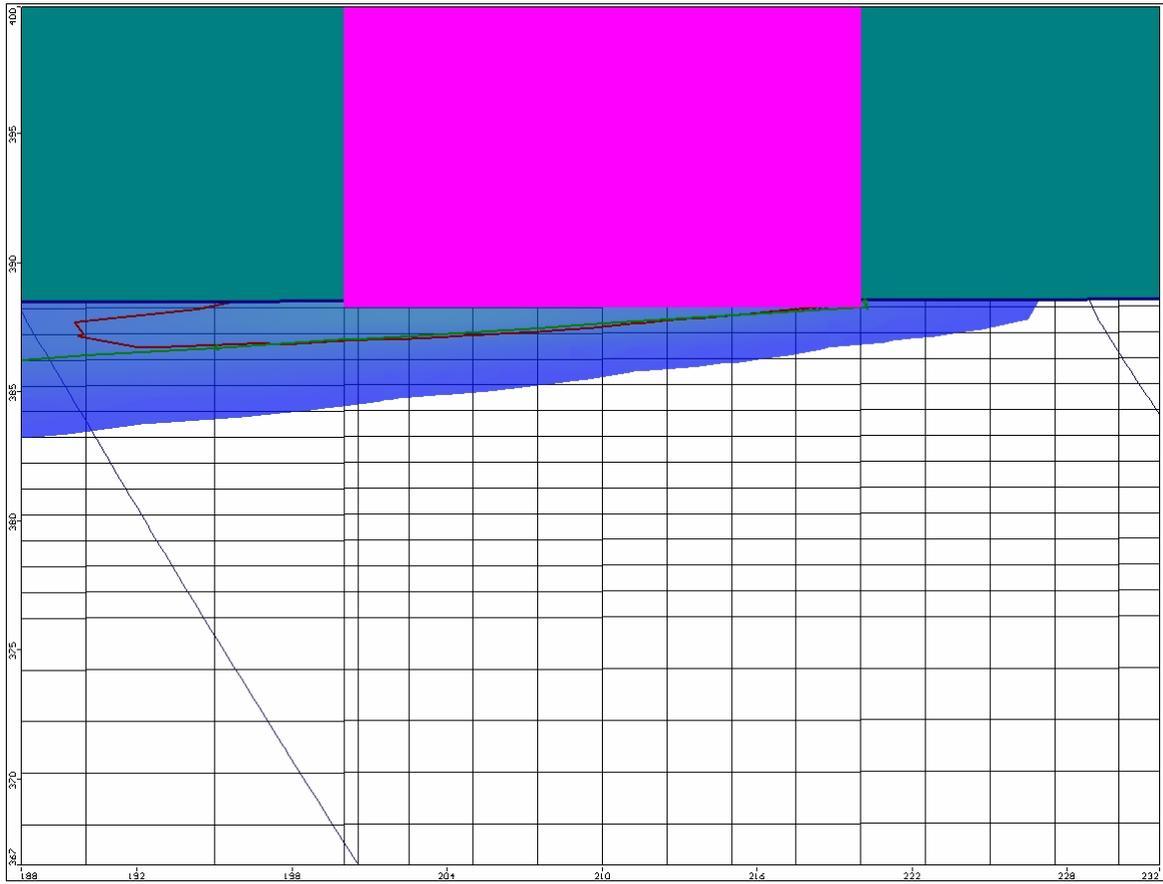


Figure 20 Dissolved Phase Plume simulated by Modflow (DF4)

Source concentration 16.5 ug/L, 5 ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 6 meter source, default site conditions except for deep aquifer. Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

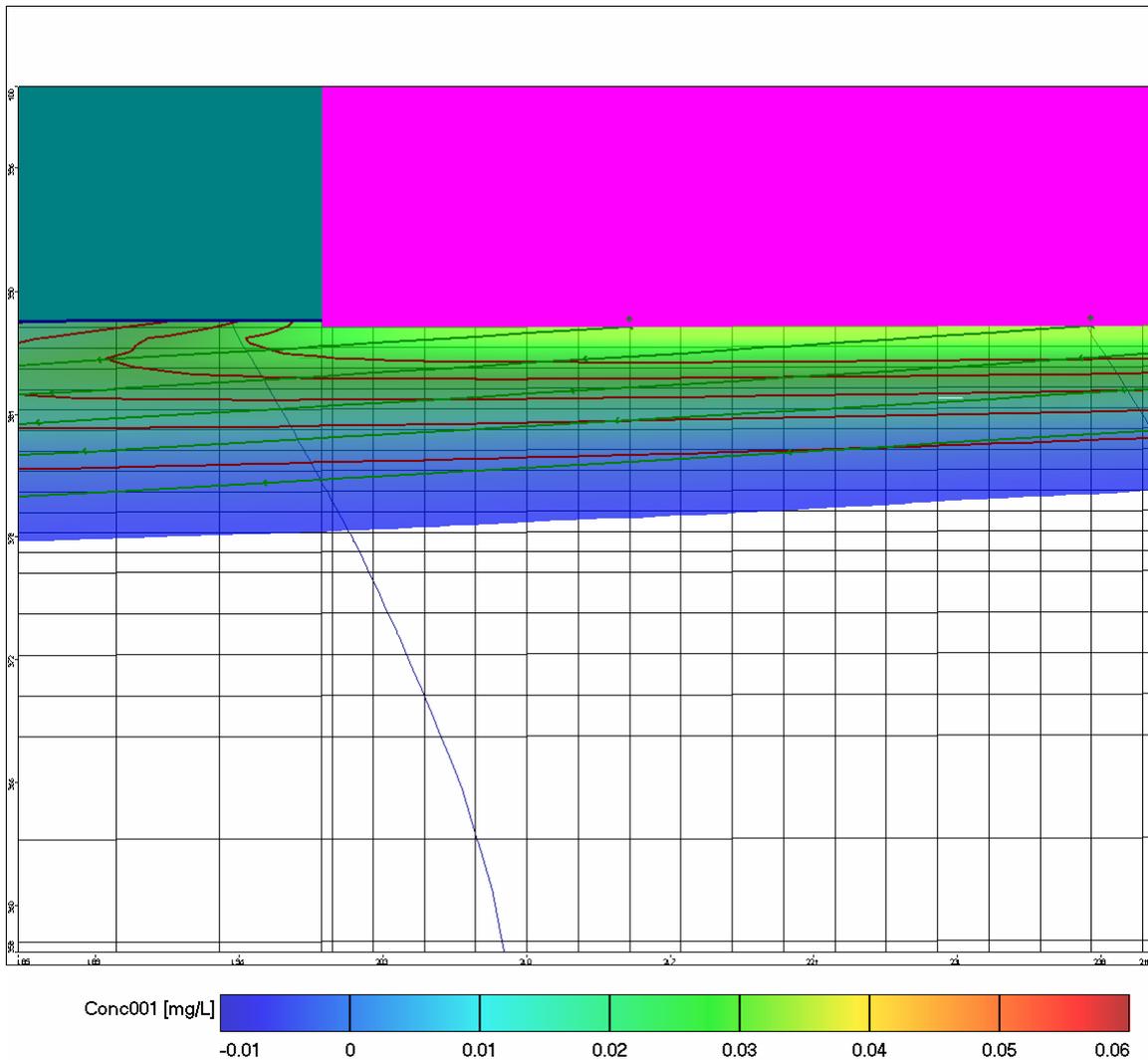


Figure 21 Dissolved Phase Plume simulated by Modflow (DAF1a)

Average benzene biodegradation rate of 0.003/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions. Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

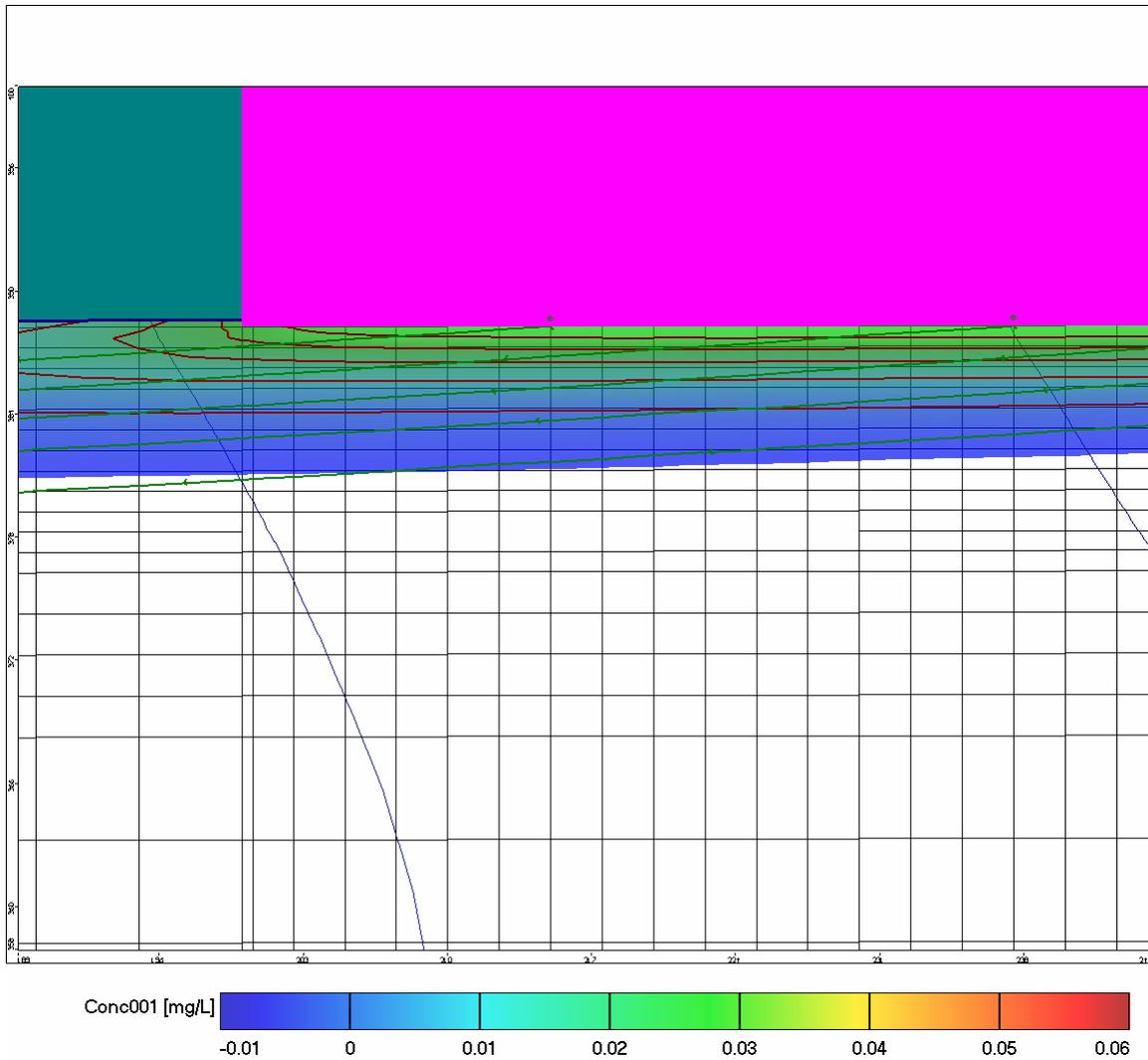


Figure 22 Dissolved Phase Plume simulated by Modflow (DAF1b)

High benzene biodegradation rate of 0.006/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions.

Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

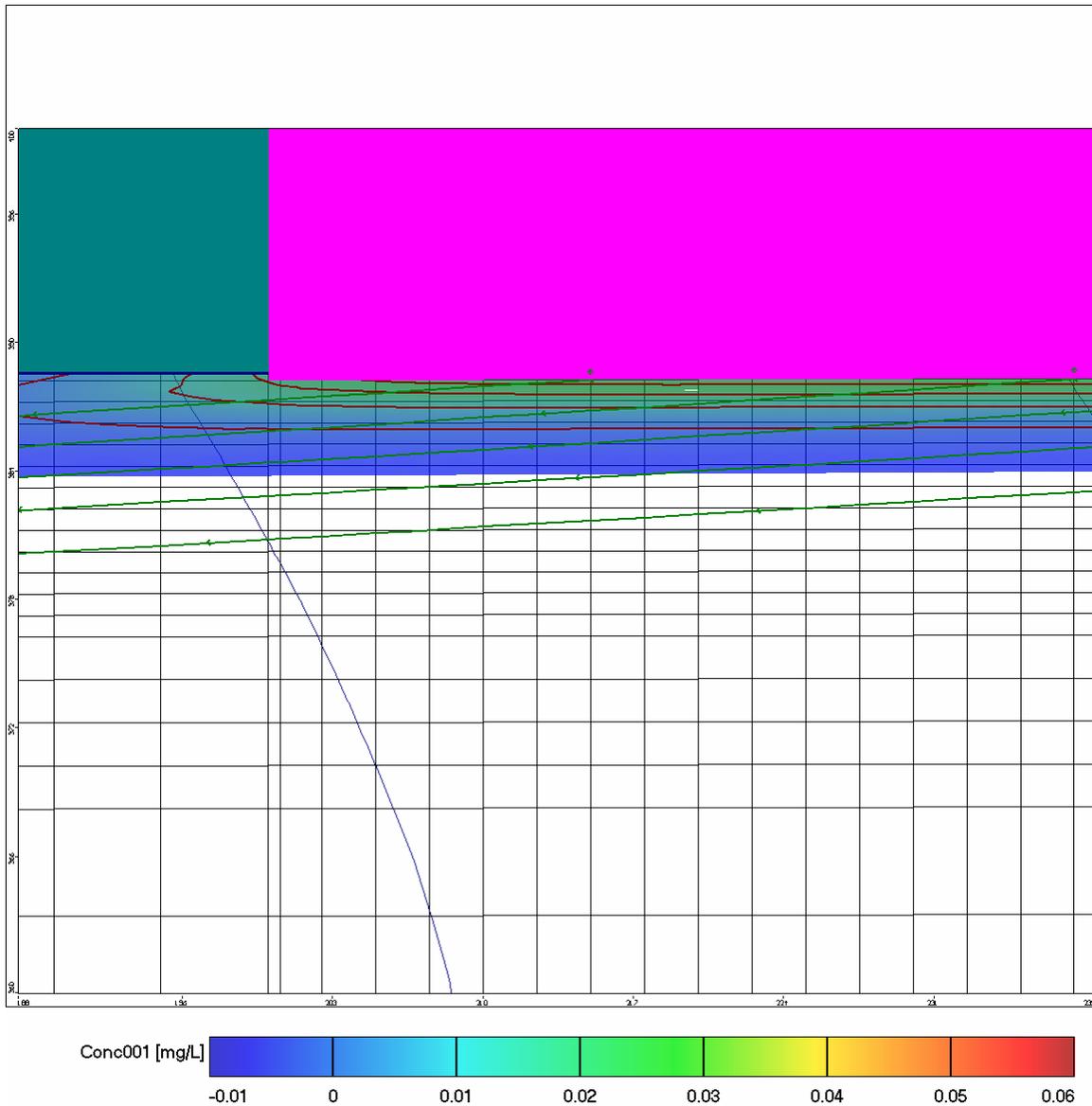


Figure 23 Dissolved Phase Plume simulated by Modflow (DAF1c)

Very high benzene biodegradation rate of 0.012/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions.

Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

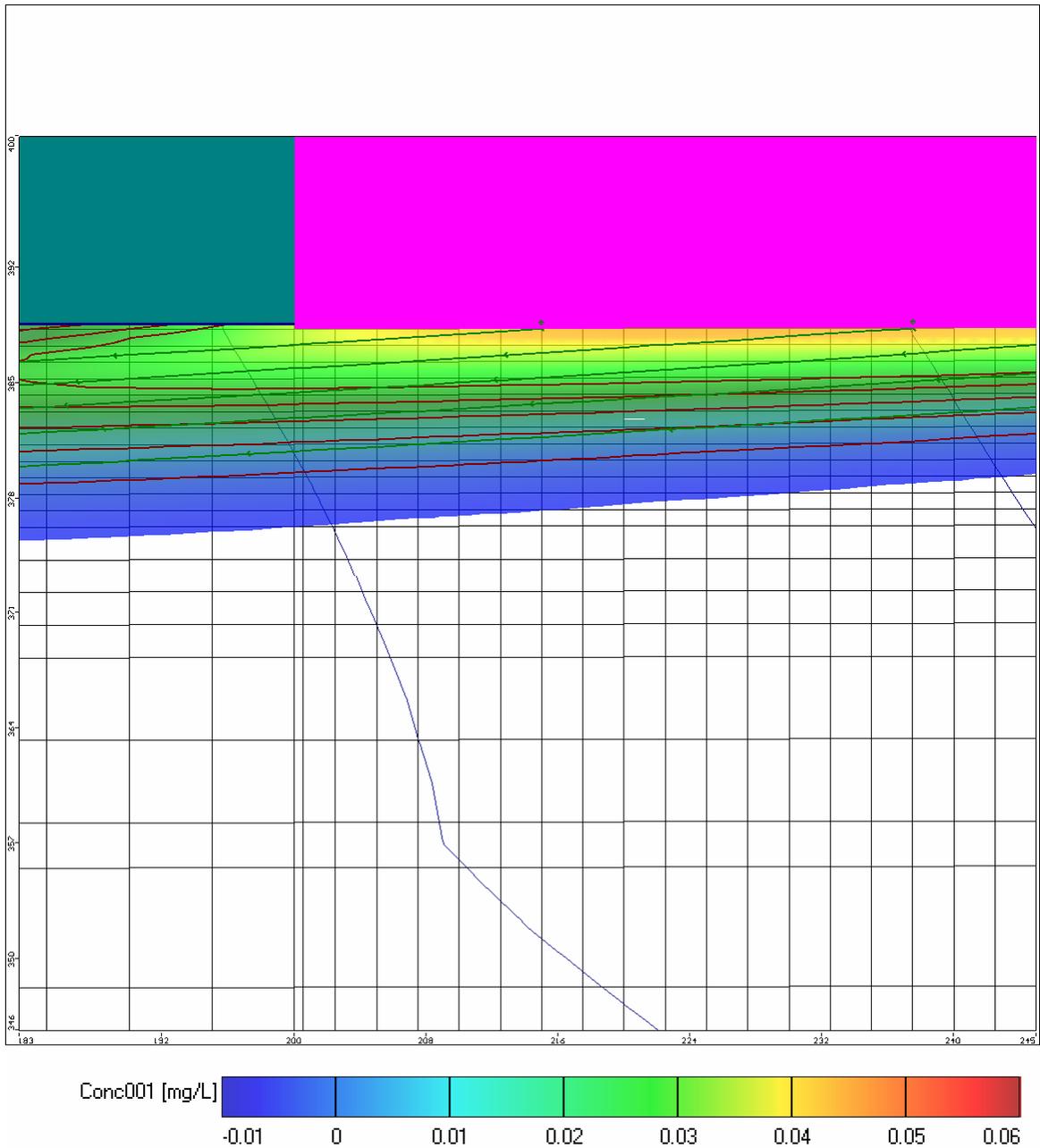


Figure 24 Dissolved Phase Plume simulated by Modflow (DAF1d)

Low benzene biodegradation rate of 0.0015/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions.

Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

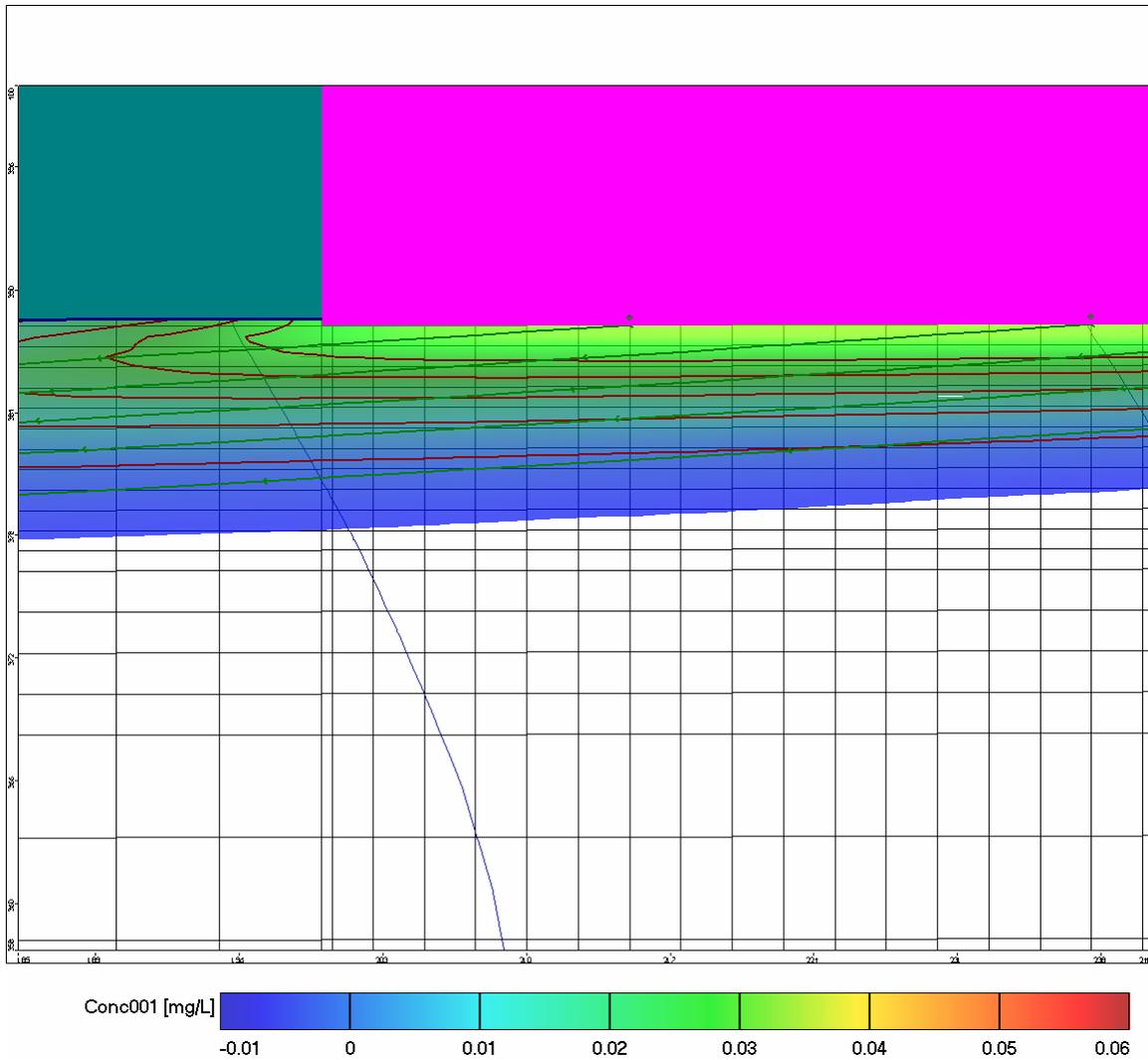


Figure 25 Dissolved Phase Plume simulated by Modflow (DAF1a)

Average benzene biodegradation rate of 0.003/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 32 meter source, default site conditions.

Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

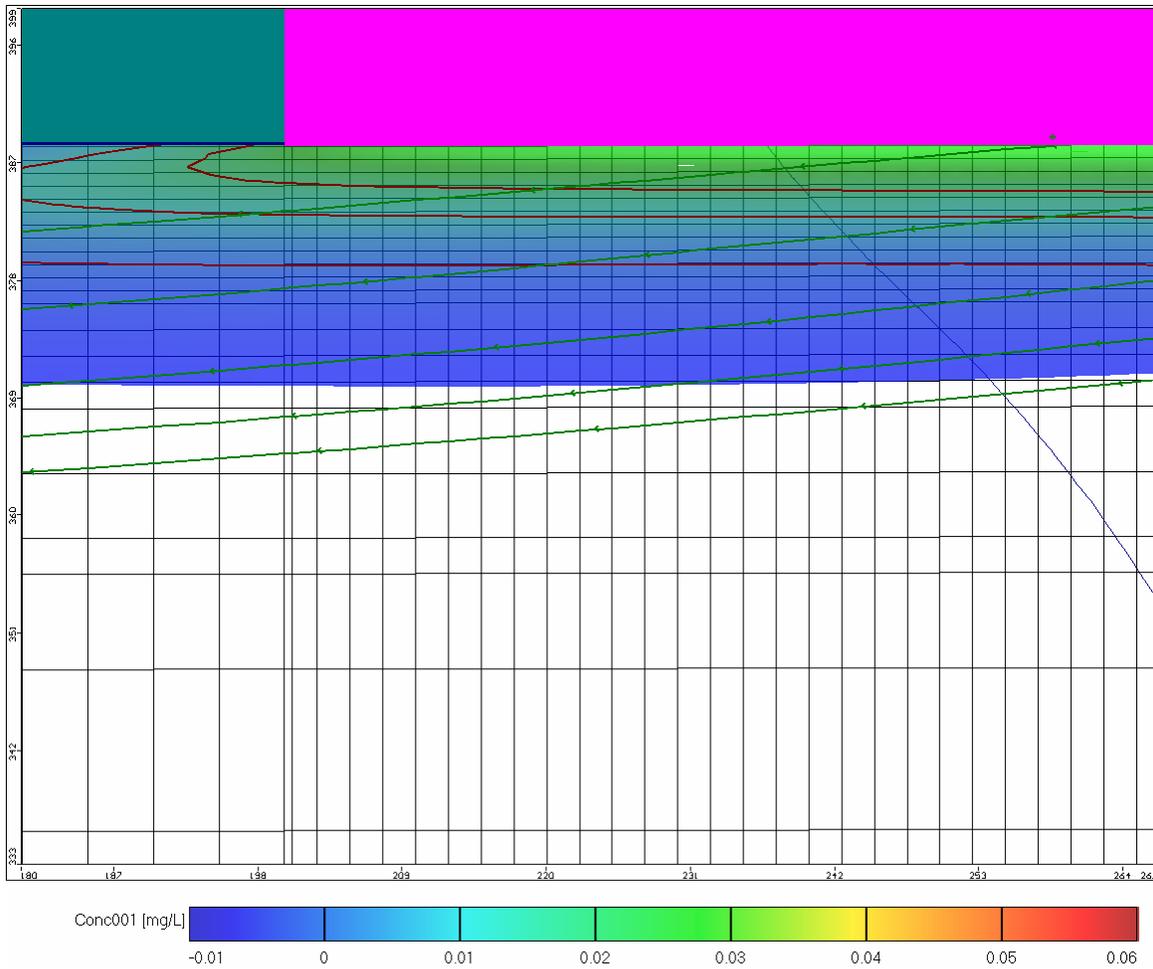


Figure 26 Dissolved Phase Plume simulated by Modflow (DAF3a)

Average benzene biodegradation rate of 0.003/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 91 meter source, other parameters are default site conditions. Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.

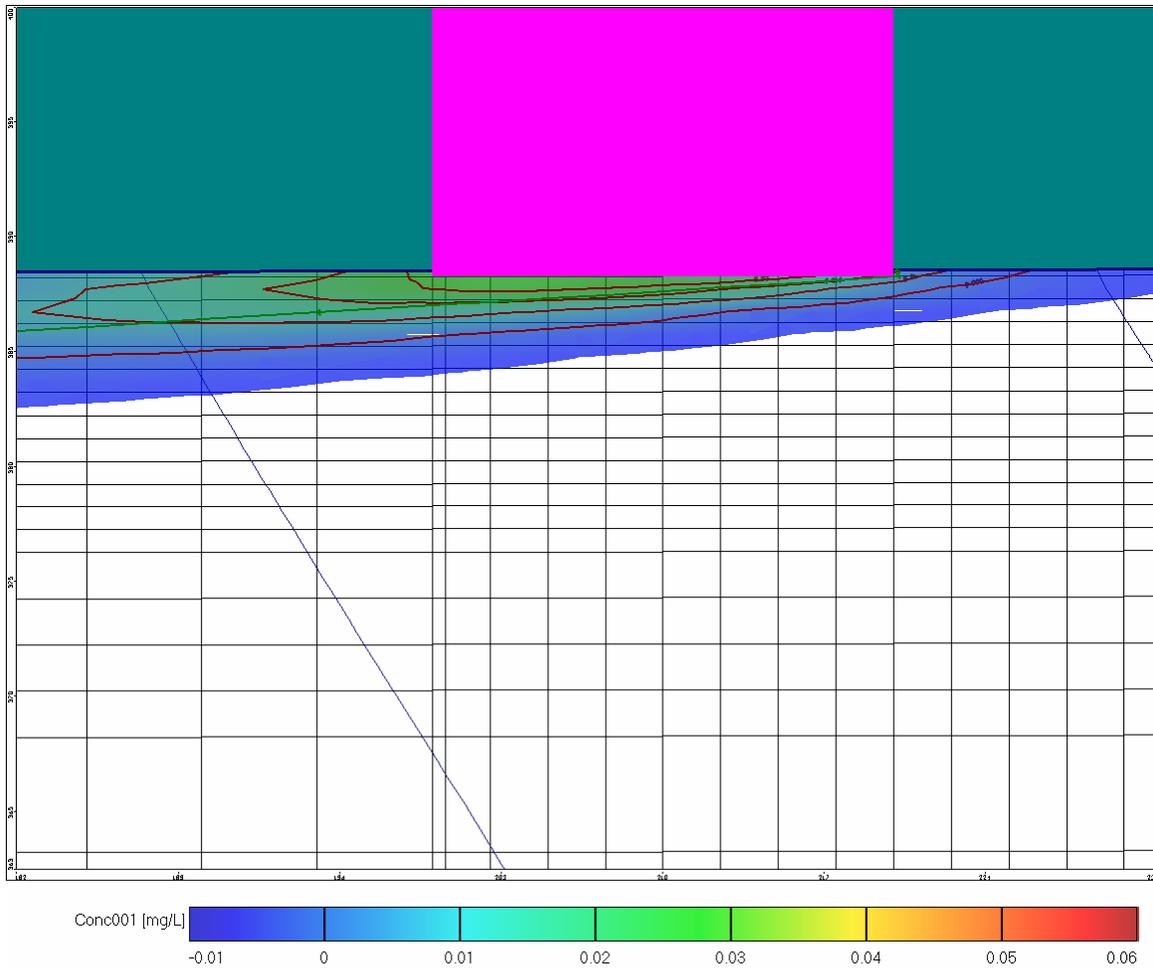


Figure 27 Dissolved Phase Plume simulated by Modflow (DAF4a)

Average benzene biodegradation rate of 0.003/day. Source concentration 66.5 ug/L, 5ug/L concentration contours, shading of dissolved benzene to 1 ug/L, 6 meter source, other parameters are default site conditions.

Source zone shown in pink, uncontaminated vadose zone shown in green, green arrows track particle flow paths—the lowest particle flow path emanates from the upgradient edge of the source area.