American Petroleum Institute

Groundwater Remediation Strategies Tool

Regulatory Analysis & Scientific Affairs Department

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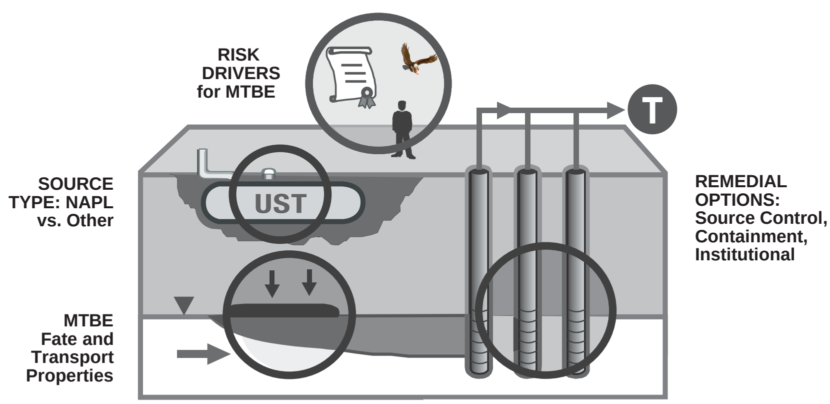

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FORWARD

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ABSTRACT

This guide provides strategies for focusing remediation efforts on 1) the change in contaminant mass flux[1] in different subsurface transport compartments (e.g. the vadose zone, smear zone or a zone within an aquifer of interest) and 2) the change in remediation timeframe.

In this approach, groundwater flow and contaminant concentration data are combined to estimate the rate of contaminant mass transfer past user-selected transects across a contaminant plume. The method provides the user with a means to estimate the baseline mass flux and remediation timeframe for various transport compartments and then evaluate how different remedies reduce the mass flux and the remediation timeframe in each transport compartment.

Results from one or more transects can be used to evaluate:

- Potential water quality impacts on downgradient water supply wells.
- The natural attenuation of the contaminant mass with distance downgradient of the source.
- The relative benefits of remedies based on their anticipated reductions in mass flux from the source to the receptor.

In addition to step-by-step instructions for the strategies, several utilities are provided including:

- Worksheets for estimating baseline mass flux and remediation timeframe and evaluating potential remedies.
- Tools for calculating mass flux.
- Resources on estimating remediation lifetime and evaluating remedy flux reduction / mass removal factors.
- Tools for evaluating how long it takes for an upgradient remedial action to affect a downgradient groundwater transect zone.

[1] Strictly speaking, mass discharge

CONTENTS

CONTENTS (continued)

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1.0 INTRODUCTION - MASS FLUX APPROACH

Potential impacts on groundwater receptors and the need for and relative benefits of alternative remedial measures may be evaluated on the basis of the mass flux of contaminants from the source zone to the receptor. This mass-based approach to site assessment and remediation has been described by various researchers (Einarson & Mackay, 2001a,b; Gallagher et al, 1995) and identified by USEPA as a key consideration in the evaluation of natural attenuation remedies (USEPA, 1998).

Under this approach, groundwater flow and contaminant concentration data are combined to estimate the rate of contaminant mass transfer (e.g., grams per day) past selected transects through an affected groundwater plume. Strictly speaking, this is a mass discharge rate; however the term “mass flux” is typically used to describe mass discharge, and this convention will be used in this document.

Results from one or more such transects can then be used to evaluate: i) potential water quality impacts on downgradient supply wells (as determined from a mass balance analysis of the supply well pumping rate), ii) the natural attenuation of the contaminant mass with distance downgradient of the source (as defined by the reduction in mass flux between transects), and iii) the relative benefits of alternative remedies (based on their anticipated reductions in mass flux from source to receptor).

The Environmental Protection Agency's Natural Attenuation Seminar (USEPA, 1998) summarized the benefits of the mass flux approach to evaluate groundwater impacts:

> ***"The reduction in the flux along the flowpath is the best estimate of natural attenuation of the plume as a whole."***
>
> ***"The flux is the best estimate of the amount of contaminant leaving the source area. This information would be needed to scale an active remedy if necessary."***
>
> ***"Flux estimate across the boundary to a receptor is the best estimate of loading to a receptor."***

Pankow and Cherry (1996) state that:

> ***"Therefore, the ultimate impact of plumes emanating from solvent DNAPL source zones can be evaluated in terms of the impact of relatively small annual mass fluxes to the receptor such as water-supply wells or surface waters. In some cases, the fluxes present significant risk to human health and/or the environment, and extensive remedial action is warranted. In other cases, the fluxes are insignificant, and remedial action would provide little or no actual environmental risk reduction."***

In summary, the use of a mass flux approach is a powerful tool for risk management (Einarson and Mackay, 2001a), one that can be used to identify high-risk sites that require higher degrees of site investigation and corrective action. This is particularly true for MTBE, as it is attenuated less in the subsurface than other plume constituents from fuel releases at many sites.

1.1 Transport Compartments

Several researchers have identified how remediation efforts can focus on individual components of a release site. For example, Gallagher, et al. (1995) developed a "Mass-Based Corrective Action" approach where the masses in different "compartments" (soil, smear zone, and dissolved plume) were estimated and the cost per pound to remediate these masses was estimated. The concept of different transport compartments is well suited for the mass flux approach, and the conceptual remediation framework described in this document is based on evaluating the vadose zone, smear zone, and several "transect zones" in the dissolved plume.

1.2 Mass Flux and Remediation Timeframe

A logical extension of the mass flux approach is to use mass flux estimates with approximations of source masses to derive order-of-magnitude estimates of remediation timeframe. With this approach, remediation efforts can focus on the change in two key process variables:

1) The change in mass flux in different transport compartments;

2) The change in remediation timeframe.

Although estimating remediation timeframe involves considerable uncertainty, relative changes in remediation timeframe can be performed with some degree of accuracy. The conceptual remediation framework described in this document discusses methods to estimate source masses and remediation timeframes in different transport compartments.

1.3 Structure of This Document

This document expands on a mass flux framework originally proposed by Einarson and MacKay (2001a) and provides tools for evaluating mass flux at affected sites. While the framework can be used for any constituent, it was originally developed with a focus on MTBE releases from petroleum release sites.

This expanded mass flux framework consists of the following elements:

- Groundwater Remediation Process Flowchart (Section 2, Figure 1);
- Baseline Mass Flux and Remediation Timeframe Tool (Section 2, Worksheet 1);
- Remediation Evaluation Tool Using Mass Flux and Remediation Timeframe (Section 2, Worksheet 2);
- Mass Flux Calculation Tools (Section 3);
- Remediation Timeframe Tools (Section 4);
- Resources for Evaluating Mass Flux and Mass Reduction Factors (Section 5);
- Tools for Evaluating Changes in Groundwater Mass Flux after Remediation (Section 6 and Appendix A); and
- Method Examples (Appendix B).

1.4 Key Definitions

***Action Level**:* Typically a concentration-based standard in either groundwater, water being extracted from a water-supply well, or a surface water quality standard.

Blending: The mixing and dilution of mass flux in either: i) a water supply well that pumps both clean water and groundwater containing a site constituent; or ii) a stream that mixes constituents in groundwater with clean surface water.

Control Point: Under a mass flux-based approach, the point where the mass flux of the constituent is to be managed. Examples include the intake of a well downgradient of a plume, or at the discharge point to a surface water body.

Flow Area: The segmented area associated with a specific concentration measurement over which an individual mass flux estimate is calculated.

Groundwater Transect Zone**:** The zone between two groundwater transects drawn across the dissolved constituent plume.

Mass Flux: The mass per time moving across a control area in a transport compartment in units of mass per time. This is also called the mass flowrate or the mass discharge rate. Note that some researchers refer to mass flux in units of mass per area per time. For this document, mass flux is used in a more general manner to mean mass per time crossing a transect. In this document, mass flux is represented by the symbol w.

Source Zone: The zone that includes both the affected soils in the vadose zone and the smear zone.

Transport Compartment: Either the vadose zone, smear zone, or a transect zone that has a constituent mass flux associated with it.

Variables Used in Worksheets 1 and 2: Variables used in Worksheets 1 and 2 take the form:

$\mathbf{A\_B_C}$

Where:

- **A** indicates the parameter represented, either the **mass flux** (**w**), the **timeframe** (**t**), the **flux reduction factor** (**rw**), or the **concentration** (**C**);
- **B** indicates the chronology of the parameter, indicating its occurrence either before remediation, as a **baseline** (**b**), or **after remediation** (**ar**); and
- **C** indicates the transport compartment, occurring at the **vadose zone** (**vd**), the **smear zone** (**sm**), the **total source zone** (**ts**), at one of four **groundwater transects** (**gw-1, gw-2, gw-3,** and **gw-4**), at the **control point** (**cp**), or at the **point-of-use** (**pou**).

2.0 GENERAL GROUNDWATER REMEDIATION PROCESS *(FLOWCHART 1)*

This groundwater remediation process works by estimating the baseline mass flux and remediation timeframe for various transport compartments, and then evaluating how different remedies reduce the mass flux and remediation timeframe in each transport compartment. The effects of an upgradient remedial action (such as remediating the vadose zone) on downgradient transport compartments is also considered. The general remediation process is shown in Figure 1.

2.1 Preliminary and Detailed Site Characterization

First, a preliminary site assessment is performed. If an action level is exceeded, then a detailed site assessment is conducted. It is recommended that characterization of MTBE sites be conducted using the methods presented in "Strategies for Characterizing Subsurface Releases of Gasoline Containing MTBE" (Nichols et al., 2000) (see box below). This document provides instructions on how to use risk-based decision making in the site characterization process.

Excerpt from "Strategies for Characterizing Subsurface Releases of Gasoline Containing MTBE" (Nichols et al., 2000, www.api.org):

Risk-informed decision making is a management strategy that adds exposure and risk considerations to the traditional technical, social, and economic components of the corrective action process. The risk-informed approach presented in this bulletin uses site-specific risk factors to help determine the appropriate level of assessment at oxygenate release sites. It includes a review of the various risk factors associated with oxygenate sources, pathways, and receptors. Based on these factors, three levels of assessment are recognized. The standard level is appropriate for the greatest number of sites: it includes moderate sample spacing with some vertical characterization, as well as horizontal characterization. The limited level is appropriate at sites with fewer risk factors: it includes relatively large sample spacing with emphasis on horizontal characterization. The detailed level is warranted for sites with the most risk factors: it requires the highest level of effort for each characterization task, with relatively close sample spacing, and extensive vertical characterization of chemical concentrations and hydraulic properties.

The appropriate level of assessment is initially determined based on receptor information, since receptor data are typically easier to obtain than source or pathway data.

Detailed information about receptors can normally be obtained from a survey of nearby wells and land uses. Receptor characterization should consider current uses and probable future uses of affected groundwater. Once receptors are characterized and an initial level of effort is established, a subsurface investigation may then be conducted to obtain detailed information about sources and pathways. The source and pathway data should be carefully reviewed as it is collected, and the level of assessment should be "upgraded" or "downgraded" accordingly. This bulletin includes a detailed overview of the tools and techniques used in the field for source and pathway characterization and subsequent monitoring at oxygenate release sites. Since traditional assessment approaches have been addressed in previous API publications, this bulletin focuses on newer technologies that allow rapid collection and field analysis of soil, soil-gas, and groundwater samples. The bulletin includes a review of the expedited site assessment process, which is particularly well suited for oxygenate assessment. It also provides a comprehensive guide to modern direct-push assessment and monitoring tools, with emphasis on their proper use at MTBE-affected sites.

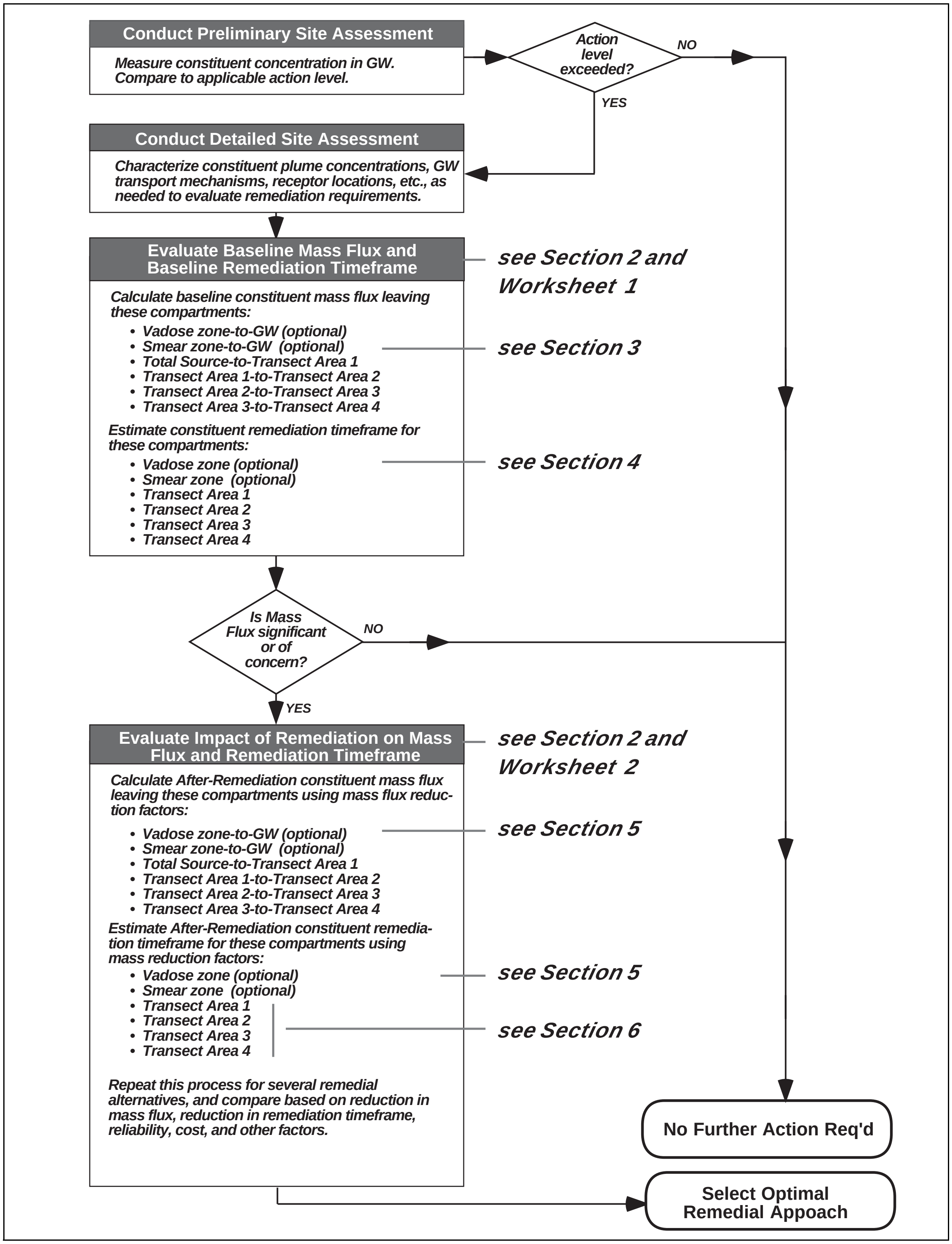

Figure 1. Groundwater Remediation Process Flowchart

2.2 Baseline Mass Flux and Remediation Timeframe Evaluation Tool (Worksheet 1)

This strategy is founded upon an analysis of constituent mass fluxes and remediation timeframes.

Baseline Mass Flux - Worksheet 1

For the baseline mass flux calculations (MFB), perform the following five steps and fill out Worksheet 1:

Step MFB-1. Calculate the Baseline Vadose Zone to Groundwater Mass Flux (w_b_{vd}) (Optional)

Using the methods and equations presented in Section 3, estimate the mass flux of the constituent leaving the vadose zone. Two main processes are typically considered: i) constituent leaving the vadose zone in recharge to water, and ii) constituent entering the groundwater via the diffusion of vapors.

Step MFB-2. Calculate the Baseline Total Source to Groundwater Mass Flux (w_b_{ts})

Using the methods and equations presented in Section 3, estimate the mass flux of the constituent leaving the entire source zone (vadose zone plus smear zone). This is typically performed using data from the closest transect of monitoring wells located downgradient of the source zone.

Step MFB-3. Calculate the Baseline Smear Zone to Groundwater Mass Flux (w_b_{sm}) (Optional)

In most cases, the Smear Zone to Groundwater Mass Flux (w_b_{sm}) is calculated by subtracting the Baseline Vadose Zone to groundwater mass flux (w_b_{vd}) from the Baseline Total Source to Groundwater Mass Flux (w_b_{ts}), or

$$w\_b_{sm} = w\_b_{ts} - w\_b_{vd}$$

Step MFB-4. Calculate the Transect Zone Mass Fluxes (w_b_{gw-1} to w_b_{gw-4})

Using the methods and equations presented in Section 3, estimate the mass flux of the constituent leaving the first transect zone (w_b_{gw-1})(the portion of the constituent plume that extends from the source zone transect; i.e., the transect used to calculate the Total Source to Groundwater flux and the next downgradient transect line).

This step is repeated for each successive downgradient Transect Zone. Although Worksheet 1 only allows a maximum of 4 Transect Zones, more can be used for an individual site by tallying the results on a separate page.

Step MFB-5. Calculate the Baseline Control Point Concentration (C_b_{cp})

Using the methods and equations presented in Section 3, determine the concentration at the control point due to blending. When an extraction well is the control point, this concentration is equal to the mass flux divided by the pumping rate of the well. When a stream is the control point, this concentration is equal to the mass flux divided by a representative low flow flowrate of the stream.

Baseline Natural Attenuation Timeframe - Worksheet 1

For the baseline remediation timeframe calculations (RTB), perform the following four steps and fill out Worksheet 1:

Step RTB-1. Estimate the Vadose Zone Natural Attenuation Timeframe (t_b_{vd}) (Optional)

Using the methods and equations presented in Section 4, estimate how long the constituent source will persist if no active remediation is performed.

Step RTB-2. Estimate the Smear Zone Natural Attenuation Timeframe (t_b_{sm}) (Optional)

Using the methods and equations presented in Section 4, estimate how long the constituent in the smear zone will persist if no active remediation is performed.

Step RTB-3. Estimate the Total Source Zone Natural Attenuation Timeframe (t_b_{ts}) (Optional)

Use the maximum value for t_b_{vd} and t_b_{sm}.

Step RTB-4. Calculate the Transect Zone Natural Attenuation Timeframe (t_b_{gw-1} through t_b_{gw-4})

Estimate the travel time from the source to the transect (divide distance from source to transect by seepage velocity and retardation factor) and add this number to the total source natural attenuation timeframe (t_b_{ts}) estimated in Step RTB-3. This will provide an order-of-magnitude approximation for how long natural attenuation alone could remediate the transect zones.

2.3 Remedy Evaluation Tool Using Mass Flux and Remediation Timeframe (Worksheet 2)

The remedy evaluation tool provides a framework for evaluating how a remedial action will reduce the mass flux at the control point, and how the remediation timeframe will be affected. A different Remedy Evaluation Tool (Worksheet 2) should be completed for every remedial alternative being considered. Successful remedial alternatives (i.e., ones that meet the required reduction in mass flux and remediation timeframe) should be compared against each other based on cost, reliability, and other factors to select the best remedial approach.

After-Remediation Mass Flux - Worksheet 2

For the after-remediation mass flux calculations (MFAR), perform the following five steps and fill out Worksheet 2:

Step MFAR-1. Calculate the After-Remediation Vadose Zone to Groundwater Mass Flux (w_ar_{vd}) (Optional)

Using the resources referenced in Section 5, estimate the Flux Reduction Factor for the Vadose Zone (rw_{vd}) that the proposed remedial alternative will achieve. For example, if soil vapor extraction (SVE) is being considered in a coarse sand, then a 90% reduction in the vadose zone MTBE mass flux could be expected (so that rw_{vd} = 0.1). However, if the remedial alternative is pump-and-treat, then the Flux Reduction Factor for the Vadose Zone would be 1.0 (no change). Flux reduction factors should reflect what can be achieved in a reasonable timeframe, such as 1-5 years.

Step MFAR-2. Calculate the After-Remediation Smear Zone to Groundwater Mass Flux (w_ar_{sm}) (Optional)

Using the resources referenced in Section 5, estimate the Flux Reduction Factor for the Smear Zone (rw_{sm}) that the proposed remedial alternative will achieve. For example, if LNAPL skimming is being considered, then a significant reduction in the smear zone mass flux would be used (such as rw_{sm} = 0.50 if the hydrogeologic conditions are appropriate for LNAPL skimming). However, if the remedial alternative is pump-and-treat in a low permeability water-bearing unit, then little reduction might be anticipated (such as rw_{sm} = 0.90). Flux reduction factors should reflect what can be achieved in a reasonable timeframe, such as 1-5 years.

Step MFAR-3. Calculate the After-Remediation Flux Reduction Factor for the Total Source Zone to Groundwater Mass Compartment (rw_{ts})

Add the after-remediation flux for the vadose zone (w_ar_{vd}) and the after-remediation flux for the smear zone (w_ar_{sm}) to get the after remediation flux for the total source-to-gw compartment (w_ar_{ts}). Then divide w_ar_{ts} by the baseline total source-to-gw flux (w_b_{ts}) to get the total source-to-gw flux reduction factor (rw_{ts}). This flux reduction factor should reflect what can be achieved by remediation in a reasonable timeframe, such as 1-5 years.

Step MFAR-4. Calculate the After-Remediation Transect Zone Mass Fluxes (w_ar_{gw-1} to w_ar_{gw-4})

Using the resources referenced in Section 5, estimate the Flux Reduction Factor for the Transect Zones (rw_{gw-1} to rw_{gw-4}) that the proposed remedial alternative will achieve. Note that the flux reduction factors are cumulative; in other words upstream flux reduction factors are reflected in downgradient flux reduction factors by multiplying them together. The goal is to get the ultimate reduction in flux.

Step MFAR-5. Calculate the Baseline Control Point Concentration (C_ar_{cp})

Using the resources referenced in Section 5, determine the Control Point Flux Reduction Factor (rw_{pou}) from any point-of-use remediation technology. Multiply this factor (if present) with all other Mass Flux reduction factors (w_ar_{ts} and w_ar_{gw-1} to w_ar_{gw-4}) to get the after-remediation mass flux to the well, and then divide by the control point flowrate to get the after-remediation control point concentration.

After-Remediation Remediation Timeframe - Worksheet 2

To evaluate the after-remediation remediation timeframe (RTAR) that the remedial technology is likely to achieve, perform the four following steps:

Step RTAR-1. Calculate the After-Remediation Vadose Zone Remediation Timeframe (t_ar_{vd}) (Optional)

Using the resources referenced in Section 5, estimate how long the source will persist if active remediation is performed.

Step RTAR-2. Calculate the After-Remediation Smear Zone Remediation Timeframe (t_ar_{sm}) (Optional)

Using the resources referenced in Section 5, estimate how long the smear zone will persist if active remediation is performed.

Step RTAR-3. Select Mass Flux Curve in Appendix A That Best Represents Source (Optional)

Using the results from Steps RTAR-1 and RTAR-2, choose either a decaying source or a step-function source that best represents the mass flux from the source during and after remediation. Refer to Section 6 and Appendix A from more information on how to make this selection.

Step RTAR-4. Estimate the Transect Zone Remediation Timeframes (t_ar_{gw-1} to t_ar_{gw-4})

Using the curve selected in Step RTAR-3, estimate how long it will take to remediate each transect zone.

When Worksheet 2 is completed, review the following information:

1. The after-remediation concentration at the control point (C_ar_{cp}) (See Step MFAR-5);
2. How long it will take to remediate each compartment (Steps RTAR-1 through RTAR-4).

Based on these factors, determine if a particular remediation alternative provides acceptable performance. If so, evaluate cost, implementability, and other factors to determine if the remediation alternative should be applied at the site.

3.0 TOOLS FOR CALCULATING MASS FLUX

The following pages contain sheets summarizing the major methods that can be used to calculate mass fluxes. These tools are provided:

Section 3.1: Groundwater Mass Flux Calculation - Transect Method
Section 3.2: Groundwater Mass Flux Calculation - Solute Transport Model Method
Section 3.3: Groundwater Mass Flux Calculation - Extraction Well Method
Section 3.4: Control Point Concentration Calculation
Section 3.5: Vadose Zone to Groundwater Mass Flux Calculation

3.1 Groundwater Mass Flux Calculation - Transect Method

Transect Method – Summary

FLUX TERM	GROUNDWATER MASS FLUX – TRANSECT METHOD
Equation	$w = \sum_{i=1}^{i=n} C_i q_i A_i CF$ w = total mass flux from source zone (g/day) (also called mass discharge)
Input Data	C_i = concentration of constituent at individual measurement point in transect (mg/L) q_i = specific discharge (also called Darcy velocity) through flow area associated with an individual measurement i (cm/sec). q_i can be calculated using: $q_i = K \cdot i$ where K = hydraulic conductivity (cm/sec) i = hydraulic gradient (cm/cm) A_i = area associated with an individual measurement (ft^2) CF = conversion factor = 80.3 (ft/cm)/(sec/day)(L/ft^3)(g/mg)
Typical Input Values	C_i = 0.001 mg/L to 10,000 mg/L (for MTBE) K (Clays) = <$1\text{x}10^{-6}$ cm/s K (Silts) = $1\text{x}10^{-6}$ to $1\text{x}10^{-3}$ cm/sec K (Silty sands) = $1\text{x}10^{-5}$ to $1\text{x}10^{-3}$ cm/sec K (Clean sands) = $1\text{x}10^{-3}$ to 1 cm/sec K (Gravel) = > 1 cm/sec i = 0.0001 to 0.01 ft/ft A_i = 100 to 100,000 ft^2

How to Calculate / Example

Estimation of mass flux across one or more transects through an affected groundwater plume involves the following principal steps:

1. ***Characterize Plume Concentrations:*** For each selected plume transect, sufficient groundwater sampling points must be available to define i) the full width and thickness of the plume and ii) the distribution of contaminant concentrations within the plume. Either single-level or multilevel groundwater monitoring points may be used for this purpose. Multilevel monitoring points can provide a more detailed three-dimensional characterization of contaminant concentrations in groundwater. However, single-level groundwater monitoring networks, while less accurate than multi-level networks, can still provide sufficient accuracy to support a mass flux analysis at many sites.

(NOTE: an alternative method is to use the concentrations from contour lines as measurement points. The locations where the transect intersects contour lines from plume maps can be used to construct flow areas for the mass flux calculations).

2. ***Characterize Groundwater Flow***: To characterize the specific discharge (q) across each plume transect, representative measurements are required for both the hydraulic flow gradient (i) and the hydraulic conductivity (K) of the flow system (where q = K x i). The groundwater flow direction and hydraulic gradient for each segment of a transect line can be determined from a potentiometric surface contour map based on static water level measurements of available sampling points. Representative measurements of the hydraulic conductivity of the groundwater-bearing unit should be obtained at one or more locations, using appropriate slug test or pumping test methods.

3. ***Select Plume Transects:*** To characterize mass flux, transects should be located at points where sufficient data are available to define affected groundwater concentrations and specific discharge, as defined in Steps 1 and 2 above. For two-dimensional data (i.e., from single-screen monitoring wells), the transect will represent a line extending across the full width of the plume, perpendicular to the direction of groundwater flow (see Figures 2 and 3). For uniform flow fields, this transect will be a straight line, but, for converging or diverging flowlines, the transect will be curvilinear in shape. For three-dimensional data (i.e., from multilevel monitoring wells), the transect line will represent a vertical plane through the groundwater plume, positioned perpendicular to groundwater flow (see Figures 4 and 5).

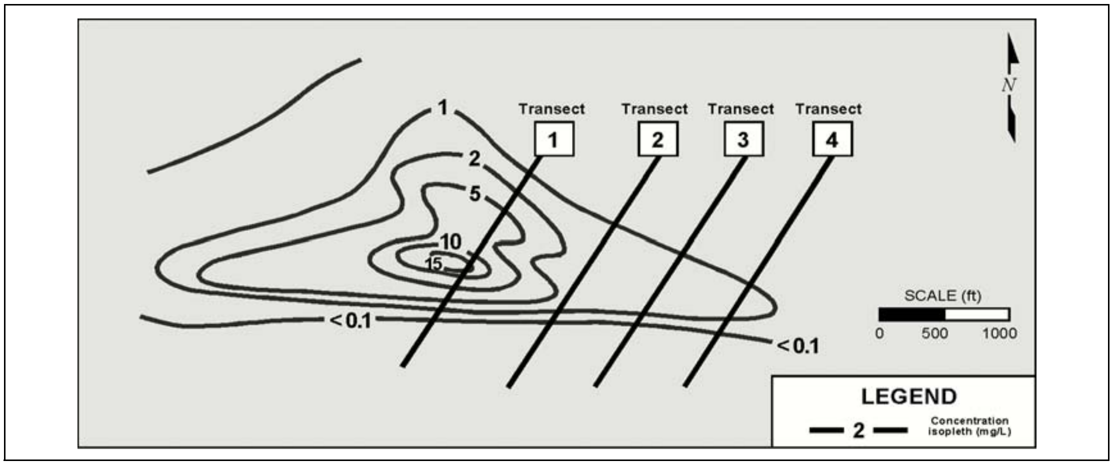

Figure 2. Example Transects through 2-D Plume Contour Map, Dover AFB, Delaware (Adapted from: Einarson, 2001)

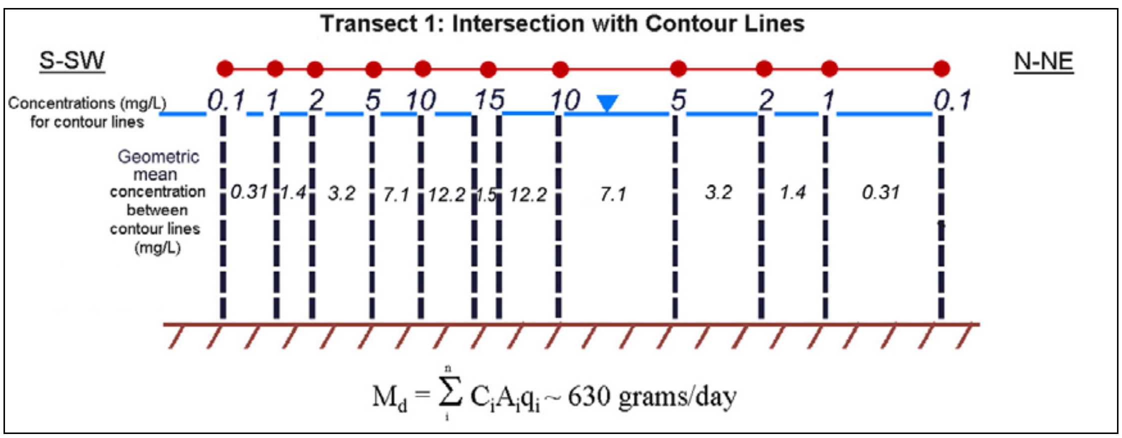

Figure 3. Concentration Profile for 2-D Transect No. 1 Based on Concentration Contours Shown in Figure 2 (Adapted from: Einarson, 2001)

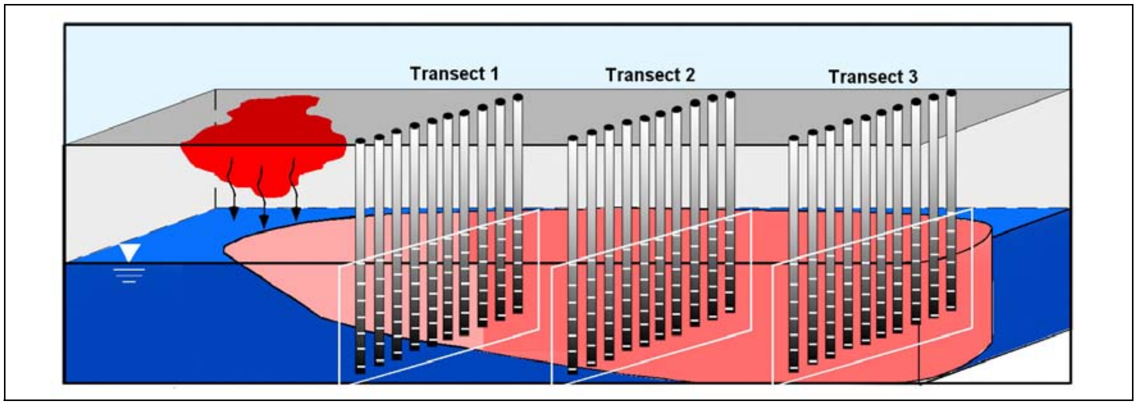

Figure 4. Example Transects through 3-D Plume Delineation

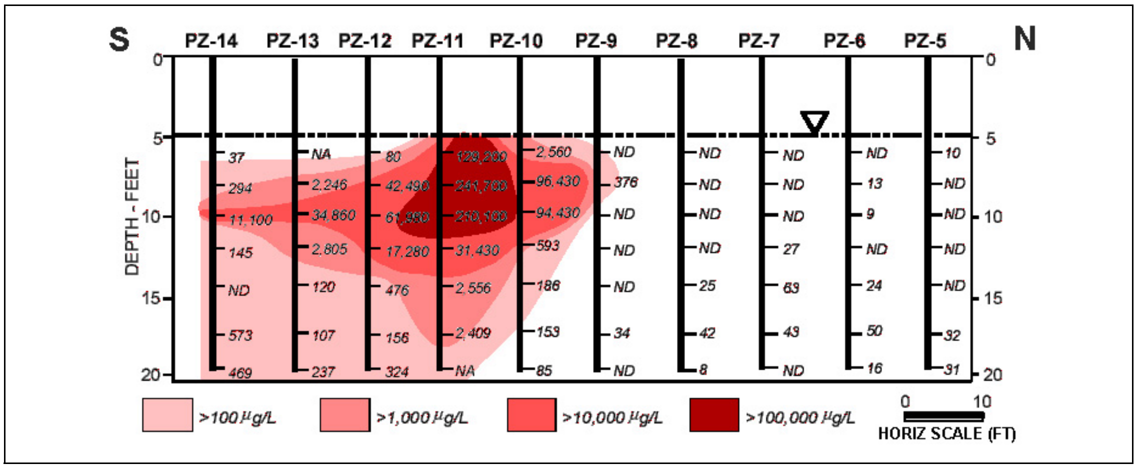

Figure 5. MTBE Concentration Profile for 3-D Transect No. 1 Shown in Figure 4
(Adapted from: Einarson, 2001)

4. ***<u>Subdivide Transects Into Subareas</u>:*** Each transect should be divided into subareas. Typically, each subarea represents a different concentration value. Two methods are commonly applied. For Method 1, subareas are divided to represent the area between concentration isopleths on a contour map of the plume. The concentration is assumed to be the geometric mean of the two contour values. For Method 2, sufficient monitoring points are located directly on the transect to construct transect subareas. The dividing line between subareas is typically halfway between the measurement points. In some cases, a combination of Method 1 and Method 2 can be applied. For three-dimensional transects, the transect plume should be subdivided into polygons bounded by contour data (Method 1) or centered on available measuring points (Method 2) (See Figures 4 and 5 for an example of Method 2).

5. ***<u>Calculate Cumulative Mass Flux Across Transect</u>:*** The total contaminant mass flux across the transect is calculated as follows:

$$w = \sum_{i=1}^{i=n} C_i q_i A_i CF$$

where:

w = total mass flux from source zone (g/day) (also called mass discharge)

C_i = concentration of constituent at flow area in transect (mg/L)

q_i = specific discharge (also called Darcy velocity) through flow area associated with an individual constituent measurement i (cm/sec). q_i can be calculated using:

$q_i = K \cdot i$ where:

K	=	hydraulic conductivity (cm/sec)
i	=	hydraulic gradient (cm/cm)
A_i	=	Flow area associated with an individual constituent measurement (ft^2)
CF	=	conversion factor = 80.3 (ft/cm)/(sec/day)(L/ft^3)(g/mg)

For the two dimensional example, mass flux is calculated as:

	C_i (mg/L)	q_i (cm/sec)	Width of Transect (ft)	Thickness of Transect (ft)	A_i (ft^2)	w_i (g/day)
1	0.31	5.00E-05	8	15	120	0.15
2	1.4	5.00E-05	5	15	75	0.42
3	3.2	5.00E-05	10	15	150	1.93
4	7.1	5.00E-05	8	15	120	3.42
5	12.2	5.00E-05	9	15	135	6.61
6	15	5.00E-05	4	15	60	3.61
7	12.2	5.00E-05	9	15	135	6.61
8	7.1	5.00E-05	19	15	285	8.12
9	3.3	5.00E-05	14	15	210	2.70
10	1.4	5.00E-05	10	15	150	0.84
11	0.31	5.00E-05	19	15	285	0.35
TOTAL						**34.8**

Table 1. Mass Flux Calculation for 2-D Transect No. 1 (see Figure 3)
(assumes K = 0.1 cm/sec, i = 0.005 ft/ft). (Adapted from: Einarson, 2001)

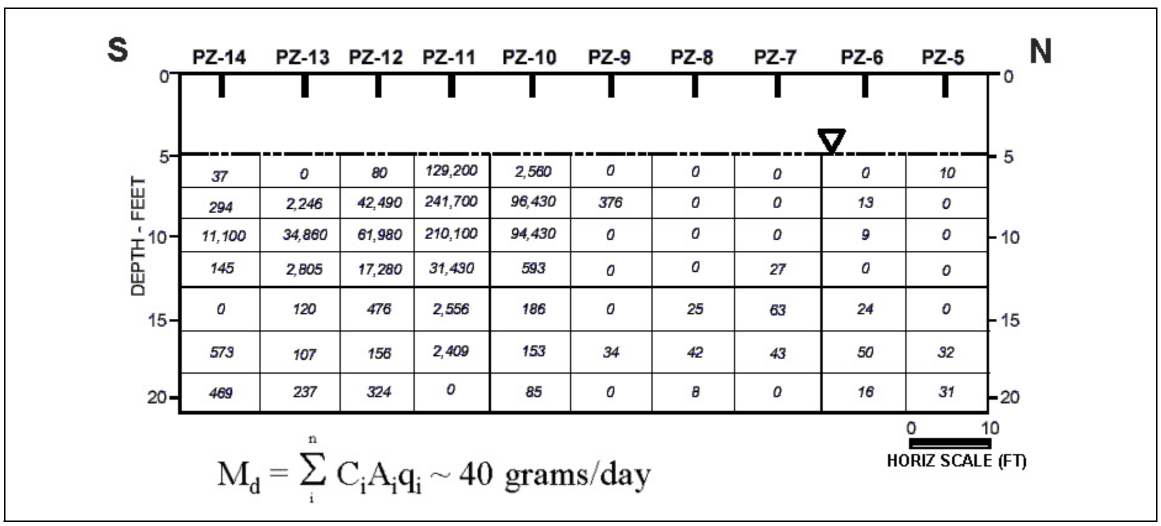

Figure 6. MTBE Concentration and Area for Each Polygon of Transect
(see Figures 4 and 5)(Adapted from: Einarson, 2001)

3.2 Groundwater Mass Flux Calculation - Solute Transport Model Method

A solute transport model can be used to estimate mass flux in groundwater. In some models, mass flux is presented directly on the output screens (e.g., BIOSCREEN, BIOCHLOR). Other models (e.g., numerical models) can provide either flow or concentrations, or both, but supplemental calculations are required to calculate a flux.

Models containing mass flux terms directly are listed below:

BIOSCREEN: An easy-to-use spreadsheet-based analytical model originally designed to be used for BTEX plumes. It can be adapted for MTBE by using the first-order decay method to simulate biodegradation or by using a first order rate constant of zero if biodegradation of MTBE is not occurring at a particular site. Mass flux is estimated from a 5x11 array of concentration values provided by the model. BIOSCREEN is a 2-D model (Newell et al, 1996).

BIOCHLOR: An easy-to-use spreadsheet-based analytical model originally designed to be used for chlorinated solvent plumes. As with BIOSCREEN, it can be adapted for MTBE by using the first-order decay method to simulate biodegradation or by using a first order rate constant of zero if biodegradation of MTBE is not occurring at a particular site. BIOCHLOR allows computation of two different degradation zones, where different first-order rate constants can be entered. Mass flux is estimated from a 5x11 array of concentration values provided by the model. BIOCHLOR is a 2-D model (Aziz et al, 2000).

3.3 Groundwater Mass Flux Calculation - Extraction Well Method

An extraction well downgradient of a source zone is pumped at a rate to capture the water flowing through the source zone. After waiting for the flow field to stabilize, the mass discharge from the well(s) is measured, which is equal to the mass flux leaving the source zone.

3.4 Control Point Concentration Calculation

Control Point Concentration – Summary

FLUX TERM	CONTROL POINT CONCENTRATION	
Equation	$$C\_b_{cp} = \frac{w_{gw-n}}{Q_{cp}}$$	
Input Data	C_b_{cp} =	concentration of constituent at the control point, such as a water-supply well or stream after blending (mg/L)
	w_{gw-n} =	The mass flux at the farthest downgradient transect (the closest transect to the control point) (g/day)
	Q_{cp} =	The total flowrate at the control point, such as the pumping rate of a water supply well, or the flowrate in a stream after blending with groundwater containing constituent (L/day)
Typical Input Values	w_{gw-n} =	0.1 to 1000 g/day
	Q_{cp} =	500 to 500,000 L/day
Comments	This is the calculation where mass flux is used to estimate the concentration of the constituent in water at the control point (such as a water supply well or stream) after blending with groundwater containing the constituent (Einarson and Mackay, 2001a).	

How to Calculate

The mass flux at a particular transect is divided by the flowrate from a pumping well at the control point. This yields a maximum concentration at the control point.

Example
Problem: Determine the control point concentration of MTBE for a transect with 100 g/day MTBE. A 100,000 L/day water supply well is located at the edge of the plume. ***Solution:*** C_b_{cp}= (100 g/day) / (100,000 L/day) * (1000 mg/g) = 1 mg/L

3.5 Vadose Zone to Groundwater Mass Flux Calculation

Vadose Zone to Groundwater Mass Flux Summary

FLUX TERM	VADOSE ZONE TO GROUNDWATER MASS FLUX
Equation	$w\_b_{vd} = \dfrac{C_T}{(\theta_{ws}/\rho_b) + k_d + H(\theta_{as}/\rho_b)} \left(\dfrac{L_1}{L_2}\right)(I_f)(A)(CF)$ where $k_d = k_{oc} f_{oc}$ and $I_f = 0.0018\ P^2$ for sandy soils (empirical relationship; results are in cm/yr) $I_f = 0.0009\ P^2$ for silty soils (empirical relationship; results are in cm/yr) $I_f = 0.00018\ P^2$ for clay soils (empirical relationship; results are in cm/yr)
Input Data	w_b_{vd} = mass flux from vadose zone (mg/yr) C_T = bulk contaminant concentration on soil mass for all phases (mg/kg) θ_{ws} = volumetric water content of surface soils (cm^3 H_2O/cm^3 soil) ρ_b = soil bulk density (g soil/cm^3 soil) k_d = soil-water distribution (partition) coefficient (cm^3 H_2O/g soil) H = Henry's law constant for contaminant (cm^3 H_2O/cm^3 air) θ_{as} = volumetric air content of vadose zone soils (cm^3 air/cm^3 soil) k_{oc} = organic carbon partition coefficient for contaminant (cm^3 H_2O/g C) f_{oc} = fraction of organic carbon (g C/g soil) L_1 = thickness of contaminated soil zone (cm) L_2 = distance from top of contaminated soil zone to top of water-bearing unit (cm) I_f = Net infiltration (cm/yr) A = area of contaminated soil zone (cm^2) P = mean annual precipitation (cm/yr) CF = conversion factor 2.74×10^{-9} (l-g-yr / cm^3 - mg - day)
Typical Input Values	C_T = 0.010 – 10,000 mg/kg (for MTBE) θ_{ws} = 0.08 to 0.38 cm^3 H_2O/cm^3 soil ρ_b = 1.7 g soil/cm^3 soil k_d = 0.072 cm^3 H_2O/g soil H = 0.024 cm^3 H_2O/cm^3 air (for MTBE) θ_{as} = 0.02 to 0.33 cm^3 air/cm^3 soil k_{oc} = $10^{1.08}$ cm^3 H_2O/g C (for MTBE) f_{oc} = 0.006 g C/g soil L_1 = 60 to 305 cm L_2 = 60 to 305 cm A = 152 to 7620 cm^2 P = 6 to 160 cm/yr

How To Calculate

The mass flux from the vadose zone to the saturated zone can be estimated using an estimated infiltration rate, the concentration of the constituent in vadose zone soils, and partitioning equations.

Example

***Problem*:** A site has an average MTBE concentration in vadose zone soils of 220 mg/kg. The site receives 100 cm of annual precipitation. The estimated soil properties are: soil bulk density of 1.7 g soil/cm^3 soil, volumetric water content = 0.08 cm^3 H2O/cm^3 soil, and volumetric air content = 0.33 cm^3 air/cm^3 soil. The contaminated soils are clean, well-graded sands. The top 61 cm of the soil is affected and is underlain by 60 cm of clean unsaturated soils before reaching the water table. The measured f_{oc} of the soil is 0.006, and the log K_{oc} value for MTBE is 1.08. The Henry's law constant for MTBE is 0.024 cm^3 H2O/cm^3 air. The source zone is 1981 cm long in the direction parallel to groundwater flow and 183 cm long in the direction perpendicular to groundwater flow.

Solution: First estimate the annual infiltration in the vadose zone. For sandy soils:
I_f = 0.0018(100)^2 = 18 cm/yr

Next, estimate the area of the contaminated soil zone:
A = (1981)(183) = 362,523 cm^2

Then estimate the vadose zone to groundwater mass flux:

$$w\_b_{vd} = \left(\frac{220}{(0.08/1.7) + 0.006\left(10^{1.08}\right) + 0.024(0.33/1.7)}\right)\left(\frac{61}{61+60}\right)(18)(362,525)\left(2.74x10^{-9}\right)$$

Vadose zone mass flux = 16.0 g/day

4.0 TOOLS FOR ESTIMATING REMEDIATION LIFETIMES

To estimate the source lifetime for use in soil and groundwater modeling, two general approaches can be used (Farhat et al., 2002):

- Extrapolate concentration vs. time trends. This can be done either for natural attenuation processes, or for a remediation system. However, several years of monitoring data are required to get a trend that is robust enough to be useful.
- Use mass-based source models to estimate remediation timeframes. With a source mass estimate and the mass flux leaving the source, an estimate of the time required to achieve a remediation goal can be estimated. This is the only method that will provide information on the impact of proposed remediation measures (i.e., trend data before a remediation system is installed will not provide any information on the remediation timeframe of the system). Note that there is considerable uncertainty with estimating mass and remediation timeframes using this method, and that the final answers will likely be an order-of-magnitude endeavor.

This section provides a list of references, resources, and tools for estimating remediation timeframes.

4.1 Key Resources - Books

<u>Natural Attenuation of Fuels and Chlorinated Solvents,</u> (Wiedemeier, et al. 1999). Source mass estimation and simple models for source decay are presented in Chapter 2, Attenuation of Sources and Formation of Plumes.

4.2 Key Resources - Data Interpretation Methods

Aqueous Concentration Ratios to Estimate Mass of Multi-Component NAPL Residual in Porous Media, (Feenstra, 1997). This method uses the preferential dissolution of the more soluble components in a multi-component NAPL to estimate NAPL mass.

"Estimation of Residual Dense NAPL Mass by Inverse Modeling", (Butcher and Gauthier, 1994). This paper presents a method and equations for estimating NAPL mass at a site on the measured flux of dissolved contaminants leaving the source zone.

4.3 Key Resources - Models

SourceDK Remediation Timeframe Decision Support System (Farhat et al., 2002). This public-domain tool contains both utilities for estimating source mass from soil and groundwater data and simple models for estimating remediation timeframes.

Evaluating Hydrocarbon Removal from Source Zones and its Effect on Dissolved Plume Longevity and Magnitude: Tools to Assess Concentration Reduction (Huntley and Beckett, 2002). This document summarizes LNAPL source zones and provides a computer tool, LNAST, to evaluate the potential benefit of source removal.

BIOSCREEN User's Manual (Newell et al., 1996). This manual reviews a simple box model for evaluating source decay.

State of Florida Natural Attenuation Decision Support System (Groundwater Services, Inc., 1997b). This proprietary software contains utilities for estimating source mass from soil and groundwater data.

4.4 Key Resources - Field Tests

"Sensitivity models and design protocol for partitioning tracer tests in alluvial aquifers", (Jin et al., 1997). This paper provides a design protocol for performing partitioning tracer tests and discusses potential interferences with the procedure.

5.0 TOOLS FOR EVALUATING FLUX REDUCTION FACTORS AND MASS REMOVAL FACTORS

Resources that can be used to estimate the performance of selected remediation technologies (i.e., mass flux reduction factors and mass reduction factors) are summarized below. Note that there is considerable uncertainty involved in predicting mass and mass flux reduction factors. Variables that contribute the most to this uncertainty include: initial mass of the release, small-scale heterogeneities in the subsurface, the distribution of any NAPL in the subsurface, and the hydrogeologic characteristics of the water-bearing unit.

5.1 Removal Technologies

TECHNOLOGY	Addresses Compartment? vd	sm	gw	Resources To Estimate Mass Flux Reduction Factor and Mass Reduction Factors	Typical Conditions Where Applicable
Soil Vapor Extraction	✓			• Johnson et al., 1990 • EPA, 1991 and 1993 • US Army Corps of Engineers Design Manual, 2002 • Wisconsin DNR, 1993	• K > 0.0001 cm/s • DTW > 10 ft • Applicable to contaminants with low vapor pressure
Excavation	✓	✓		• Church, 1981 • EPA, 1991	DTW > 10 ft DOI < 20 ft
Air Sparging			✓	• American Petroleum Institute, 1995 • Leeson, 2001 • US Army Corps of Engineers, 1997	• K > 0.0001 cm/s • DTW > 10 feet • Homogeneous formations • Saturated water-bearing units
Pump & Treat			✓	• National Research Council, 1994 • USEPA, 1996 • Suthersan, 1997	• K > 0.0001 cm/s
LNAPL Skimming		✓		• API, 1999 • API, 2002 • API, 2003 • Huntley et al., 2002	• DOI < 20 ft • Useful for higher LNAPL production levels (e.g., gallons/day), particularly in high permeability gw units
LNAPL Absorbents		✓			• Useful for small LNAPL accumulations or slow LNAPL recharge rates (< 1" in well)
Total Combined Fluids Pumping		✓	✓		• K > 0.0001 cm/s
Continuous Multi-Phase Extraction – Bioslurping	✓	✓	✓	• AFCEE, 1995 • Battelle, 1996 • Hoeppel et al., 1998 • Miller, 1996 • Place et al., 2001	• $10^{-5} < K < 10^{-3}$ cm/s • DTW < 25 ft
Natural Attenuation			✓	• ASTM, 1998 • Wiedemeier et al., 1999	• Usually long time horizon • No impacted receptor • Affected plume is stable or diminishing

K = hydraulic conductivity, DTW = Depth to Water, DOI = Depth of Impact
vd = vadose zone, sm = smear zone, gw = groundwater

5.2 Containment Technologies

TECHNOLOGY	Addresses Compartment? vd	sm	gw	Resources To Estimate Mass Flux Reduction Factor and Mass Reduction Factors	Typical Conditions Where Applicable
Hydraulic Containment			✓	• EPA, 1996 and 1997	• K > 0.0001 cm/sec
Barrier Walls/ Cut-Off Trench			✓	• Davidson et al., 1992 • EPA, 1998 • McCandless et al., 1987 • Rumer et al., 1995 • Spooner et al., 1985	• DOI < 50 ft
Caps/Covers	✓			• EPA ,1987 and 1993	
Biological Barriers			✓	• Salanitro et al., 2000	

5.3 Remediation References

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6.0 TOOLS FOR EVALUATING CHANGES IN GROUNDWATER MASS FLUX AFTER REMEDIATION

To evaluate how long it takes an upgradient remedial action to affect a downgradient groundwater transect zone, 180 different mass flux vs. distance curves are provided in Appendix A. Each curve has a different combination of source type, hydrogeologic data, and timing assumptions. These curves are divided into three broad groups based on source type, and can be used in the following ways:

TYPE OF SOURCE	When Applicable for BASELINE Evaluation (Steps RTB-1 to RTB-4)	When Applicable for AFTER-REMEDIATION Evaluation (Steps RTAR-1 to RTAR-4)
Constant Source	Low mass flux relative to source mass	Not applicable
Decaying Source	Moderate source mass flux relative to source mass	Remediation alternative quickly removes source, then remaining source slowly dissipates
Step-Function Source	High mass flux relative to source mass but with some residual source that persists	Remediation alternative that quickly removes some source mass, but remaining source mass produces constant concentrations

6.1 How to Use the Mass Flux vs. Distance Curves

The goal for using these curves is to evaluate how long it takes an upgradient remedial action to affect a downgradient groundwater transect zone. To use the mass flux vs. distance curves, select the condition that best matches your site conditions:

1. Select source type:

- ***Constant Source*.** Use for evaluating baseline (no remediation) conditions at sites with relatively constant source concentrations over time.
- ***Decaying Source*.** Use for evaluating sites where natural attenuation or a remediation system is reducing the source concentration quickly at first, then more slowly.
- ***Step-Function Source*.** Use for evaluating sites where natural dissolution of the source or a remediation system quickly reduces the source flux by some percentage, and then the reduced source is relatively constant over a long period of time. Examples are a partial excavation of the source, or an intensive remediation effort that removes some fraction of the source quickly, but leaves some fraction behind as a constant source.

2. Select source characteristic. Select source type:

- **Constant Source.** No characteristic to select.
- ***Decaying Source.*** The key factor to consider when selecting a decaying source graph to use is how quickly the source is being decayed. This is represented by the source decay half-life. This guide lets you select a source decay half-life of either 1, 5, or 10 years. For example, if natural attenuation is reducing the MTBE concentration in a source zone by half every 5 years, use the mass flux vs. distance curve for a 5-year source decay half-life. If multi-phase extraction is reducing the MTBE concentration in a source zone by half every 1 year, use the mass flux vs. distance curve for a 1-year source decay half-life.

- ***Step-Function Source.*** The key factor to consider when selecting which step-function source graph to use is the duration when the source is at full strength (this guide lets you select either 1 or 5 years for a full-strength source) and what percent reduction in flux does the remediation system achieve (currently this guide lets you select either a 10% reduction in flux or a 90% reduction in flux).

(The source mass flux vs. time pattern is shown in the top left panel of each page of mass flux vs. distance graphs in Appendix A.)

3. **Select biodegradation characteristics in the plume.** You can choose to have no biodegradation downgradient of the plume (λ = 0) or moderate biodegradation (λ = 0.693 yrs, equivalent to a 1-year biodegradation half-life).

4. **Select the groundwater seepage velocity for your site.** Each page of graphs in Appendix A has five different groundwater seepage velocities to choose from:

   - 50 ft/yr
   - 75 ft/yr
   - 100 ft/yr
   - 150 ft/yr
   - 200 ft/yr

With Steps 1-4 completed, you can choose the appropriate graph from Appendix A that best matches your site. (Use the index of all the curves below, or use the index at the beginning of Appendix A to find the appropriate curve).

5. **Select the distance from the source where you would like to know how the flux changes over time.** This is the x-axis on each graph.

6. **Select the time when you would like to evaluate the mass flux** (the mass flux is always expressed as a percentage of the original pre-remediation mass flux at the source). Each graph has four curves representing these time conditions:

   - 1 year after original release
   - 5 years after original release
   - 10 years after original release
   - 20 years after original release

With Steps 1-6 completed, you can now determine how much the original baseline mass flux from the source has been or will be reduced at a certain point in the plume and at a certain distance after the source has been released. The graphs allow you to account for changes in the original source mass flux due to natural attenuation or due to remediation.

Each source term is discussed in more detail below.

6.2 Constant Source

The first example mass flux relationship (Figure 7) shows how mass flux changes downgradient of a constant source of constituents to groundwater at a site with 100 ft/yr groundwater seepage velocity, no sorption, no biodegradation, no remediation of the source, and typical estimates for hydrodynamic dispersion (longitudinal and transverse dispersion only). As can be seen, the constant source results in a plume that gets longer over time, with only limited attenuation from dispersion.

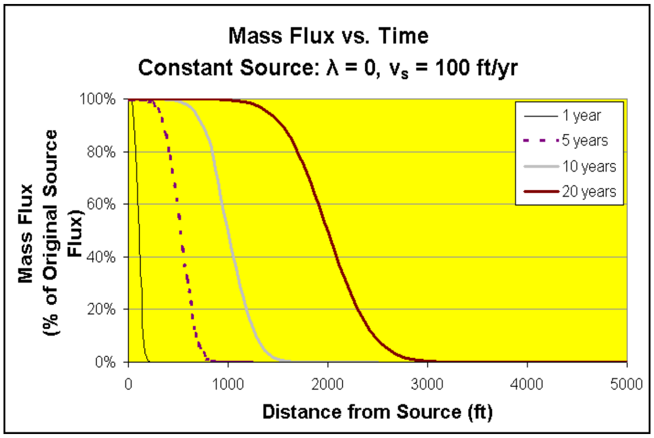

Figure 7. Change in Mass Flux Downgradient of Constant Source (no remediation, v_s = 100 ft/yr, longitudinal dispersion based on plume length and Xu and Eckstein relationship, R = 1, and λ = 0)

This graph shows how the mass flux changes over time and over distance downgradient of a constant source of constituents to groundwater. For example, if a constant source is released starting at year 0, the mass flux at a point 1000 ft downgradient of the source will be about 50% of the source mass flux after 10 years, but only because the plume has not yet reached this point. After 20 years, however, the full strength plume has reached the 1000 ft point, and the mass flux is about 99% of the source mass flux, (i.e., dispersion reduces the mass flux by only 1%).

Appendix A contains additional constant source graphs for the following cases:

SOURCE TYPE	Seepage Velocity (ft/yr)	Plume Biodegradation Rate (per year)	Page Number
Constant Source	50	No biodegradation (λ = 0)	A-5
	75	No biodegradation (λ = 0)	A-5
	100	No biodegradation (λ = 0)	A-5
	150	No biodegradation (λ = 0)	A-5
	200	No biodegradation (λ = 0)	A-5
Constant Source	50	Moderate biodegradation (λ = 0.693/yr)	A-6
	75	Moderate biodegradation (λ = 0.693/yr)	A-6
	100	Moderate biodegradation (λ = 0.693/yr)	A-6
	150	Moderate biodegradation (λ = 0.693/yr)	A-6
	200	Moderate biodegradation (λ = 0.693/yr)	A-6

6.3 Decaying Source

As the source weathers or is remediated, the mass flux is reduced significantly at some point in time. At some sites this can be simulated with a first order decay relationship for the source concentration. (Note this source decay is not the same as the decay of a constituent in the dissolved phase; see Newell et al., 2002). Figure 8 shows an example of a source where the source mass flux is reduced in half every year (the source decay rate constant is k_s = 0.693/yr, equivalent to a source decay half-life of 1 year). The curves in Figure 8 also are based on a groundwater seepage velocity of 100 ft/yr, no sorption, no biodegradation of constituents in the plume (λ = 0), and typical estimates for hydrodynamic dispersion (longitudinal and transverse dispersion only). As can be seen, the decaying source results in a plume that has significantly smaller downgradient mass flux compared to the constant source scenario.

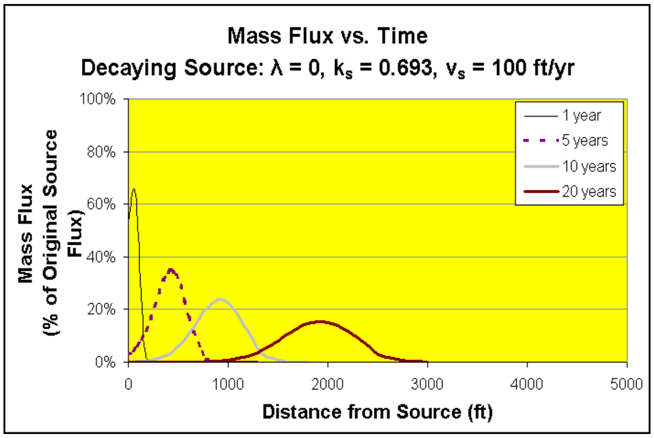

Figure 8. Change in Mass Flux Downgradient of Decaying Source (source decay constant k_s = 0.693 per year, equivalent to a source half-life of 1 year, v_s = 100 ft/yr, longitudinal dispersion based on plume length and Xu and Eckstein relationship, R = 1, and λ = 0.)

For example, if a remediation technology such as air sparging reduced the mass flux by half every year, then the mass flux at a point 1000 ft downgradient of the source would be 22% of the initial mass flux at the source after 10 years, and about 1% after 20 years. Note that this source decay is assumed to start immediately after the release.

Appendix A contains additional decaying source graphs for the following cases:

SOURCE TYPE	Source Halflife ($t_{\text{source half-life}}$, years)	Seepage Velocity (ft/yr)	Plume Biodegradation Rate (per year)	Page Number
Decaying Source	1	50	No biodegradation (λ = 0)	A-7
	1	75	No biodegradation (λ = 0)	A-7
	1	100	No biodegradation (λ = 0)	A-7
	1	150	No biodegradation (λ = 0)	A-7
	1	200	No biodegradation (λ = 0)	A-7
Decaying Source	1	50	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	75	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	100	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	150	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	200	Moderate biodegradation (λ = 0.693/yr)	A-8
Decaying Source	5	50	No biodegradation (λ = 0)	A-9
	5	75	No biodegradation (λ = 0)	A-9
	5	100	No biodegradation (λ = 0)	A-9
	5	150	No biodegradation (λ = 0)	A-9
	5	200	No biodegradation (λ = 0)	A-9

SOURCE TYPE	Source Halflife ($t_{source\ half-life}$, years)	Seepage Velocity (ft/yr)	Plume Biodegradation Rate (per year)	Page Number
Decaying Source	5	50	No biodegradation (λ = 0)	A-10
	5	75	No biodegradation (λ = 0)	A-10
	5	100	No biodegradation (λ = 0)	A-10
	5	150	No biodegradation (λ = 0)	A-10
	5	200	No biodegradation (λ = 0)	A-10
Decaying Source	10	50	Moderate biodegradation (λ = 0.693/yr)	A-11
	10	75	Moderate biodegradation (λ = 0.693/yr)	A-11
	10	100	Moderate biodegradation (λ = 0.693/yr)	A-11
	10	150	Moderate biodegradation (λ = 0.693/yr)	A-11
	10	200	Moderate biodegradation (λ = 0.693/yr)	A-11
Decaying Source	10	50	No biodegradation (λ = 0)	A-12
	10	75	No biodegradation (λ = 0)	A-12
	10	100	No biodegradation (λ = 0)	A-12
	10	150	No biodegradation (λ = 0)	A-12
	10	200	No biodegradation (λ = 0)	A-12

6.4 Step-Function Source

If a constant source was diminished but not totally removed, then the mass flux downgradient of the source would be reduced compared to the constant source case. In the example mass flux vs. distance graph shown in Figure 9, constituents are released in the groundwater at full strength for 5 years, and then continues indefinitely at 10% of the original source mass flux.

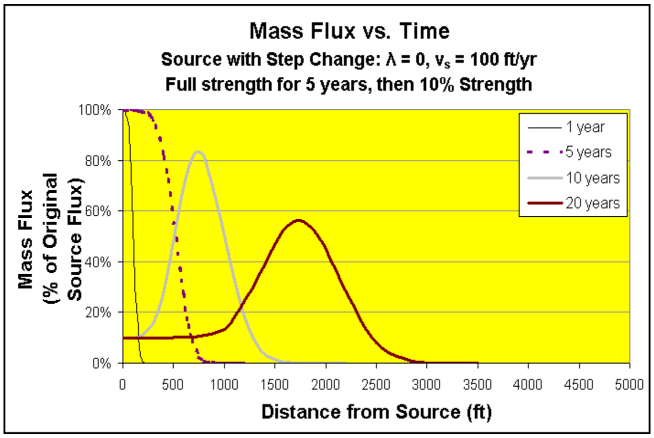

Figure 9. Change in Mass Flux Downgradient of Step-Function Source (source pattern: 5 years at full strength, then remains constant at 10% strength), v_s = 100 ft/yr, longitudinal dispersion based on plume length and Xu and Eckstein relationship, R = 1, and λ = 0.)

This graph can be used to estimate what the mass flux would be if the source is reduced by 90% (to 10% strength) after 5 years of sourcing, either due to natural depletion of the constituents in the source compartments, or due to remediation efforts. For example, if a remediation technology such as excavation removes 90% of an MTBE source 5 years after the original release, followed by a small but constant residual source at 10% of the original flux, then the mass flux at a point 1000 ft downgradient of the source would be 60% of the initial source mass flux after 10 years, and about 11 % after 20 years.

Appendix A contains additional step-function source graphs for the following cases:

SOURCE TYPE	Seepage Velocity (ft/yr)	Plume Biodegradation Rate (per year)	Page Number
Full Strength for 1 year, then 90% strength	50	No biodegradation (λ = 0)	A-13
	75	No biodegradation (λ = 0)	A-13
	100	No biodegradation (λ = 0)	A-13
	150	No biodegradation (λ = 0)	A-13
	200	No biodegradation (λ = 0)	A-13
Full Strength for 5 years, then 10% strength	50	No biodegradation (λ = 0)	A-14
	75	No biodegradation (λ = 0)	A-14
	100	No biodegradation (λ = 0)	A-14
	150	No biodegradation (λ = 0)	A-14
	200	No biodegradation (λ = 0)	A-14

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APPENDIX A – MASS FLUX vs. DISTANCE CURVES

Groundwater Remediation Strategies Tool
American Petroleum Institute

How to use the Mass Flux vs. Distance Curves

The goal for using these curves is to evaluate how long it takes an upgradient remedial action to affect a downgradient groundwater transect zone. To use the mass flux vs. distance curves, select the condition that best matches your site conditions:

1. Select source type:

- ***Constant Source*.** Use for evaluating baseline (no remediation) conditions at sites with relatively constant source concentrations over time.
- ***Decaying Source*.** Use for evaluating sites where natural attenuation or a remediation system is reducing the source concentration quickly at first, then more slowly.
- ***Step-Function Source*.** Use for evaluating sites where natural dissolution of the source or a remediation system quickly reduces the source flux by some percentage, and then the reduced source is relatively constant over a long period of time. Examples are a partial excavation of the source, or an intensive remediation effort that removes some fraction of the source quickly, but leaves some fraction behind as a constant source.

2. Select source characteristic. Select source type:

- ***Constant Source.*** No characteristic to select.
- ***Decaying Source.*** The key factor to consider when selecting a decaying source graph to use is how quickly the source is being decayed. This is represented by the source decay half-life. This guide lets you select a source decay half-life of either 1, 5, or 10 years. For example, if natural attenuation is reducing the MTBE concentration in a source zone by half every 5 years, use the mass flux vs. distance curve for a 5-year source decay half-life. If multi-phase extraction is reducing the MTBE concentration in a source zone by half every 1 year, use the mass flux vs. distance curve for a 1-year source decay half-life.
- ***Step-Function Source.*** The key factor to consider when selecting which step-function source graph to use is the duration when the source is at full strength (this guide lets you select either 1 or 5 years for a full-strength source) and what percent reduction in flux does the remediation system achieve (currently this guide lets you select either 10% reduction in flux or a 90% reduction in flux).

(The source mass flux vs. time pattern is shown in the top left panel of each page of mass flux vs. distance graphs in Appendix A.)

3. Select biodegradation characteristics in the plume. You can choose to have no biodegradation downgradient of the plume (λ= 0) or moderate biodegradation (λ = 0.693 yrs, equivalent to a 1-year biodegradation half-life).

4. **Select the groundwater seepage velocity for your site.** Each page of graphs in Appendix A has five different groundwater seepage velocities to choose from:

   - 50 ft/yr
   - 75 ft/yr
   - 100 ft/yr
   - 150 ft/yr
   - 200 ft/yr

With Steps 1-4 completed, you can choose the appropriate graph from Appendix A that best matches your site. (Use the index of all the curves below, or use the index at the beginning of Appendix B to find the appropriate curve).

5. **Select the distance from the source where you would like to know how the flux changes over time.** This is the x-axis on each graph.

6. **Select the time when you would like to evaluate the mass flux (the mass flux is always expressed as a percentage of the original pre-remediation mass flux at the source).** Each graph has four curves representing these time conditions:

   - 1 year after original release
   - 5 years after original release
   - 10 years after original release
   - 20 years after original release

With Steps 1-6 completed, you can now determine how much the original baseline mass flux from the source has been or will be reduced at a certain point in the plume and at a certain distance after the source has been released. The graphs allow you to account for changes in the original source mass flux due to natural attenuation or due to remediation.

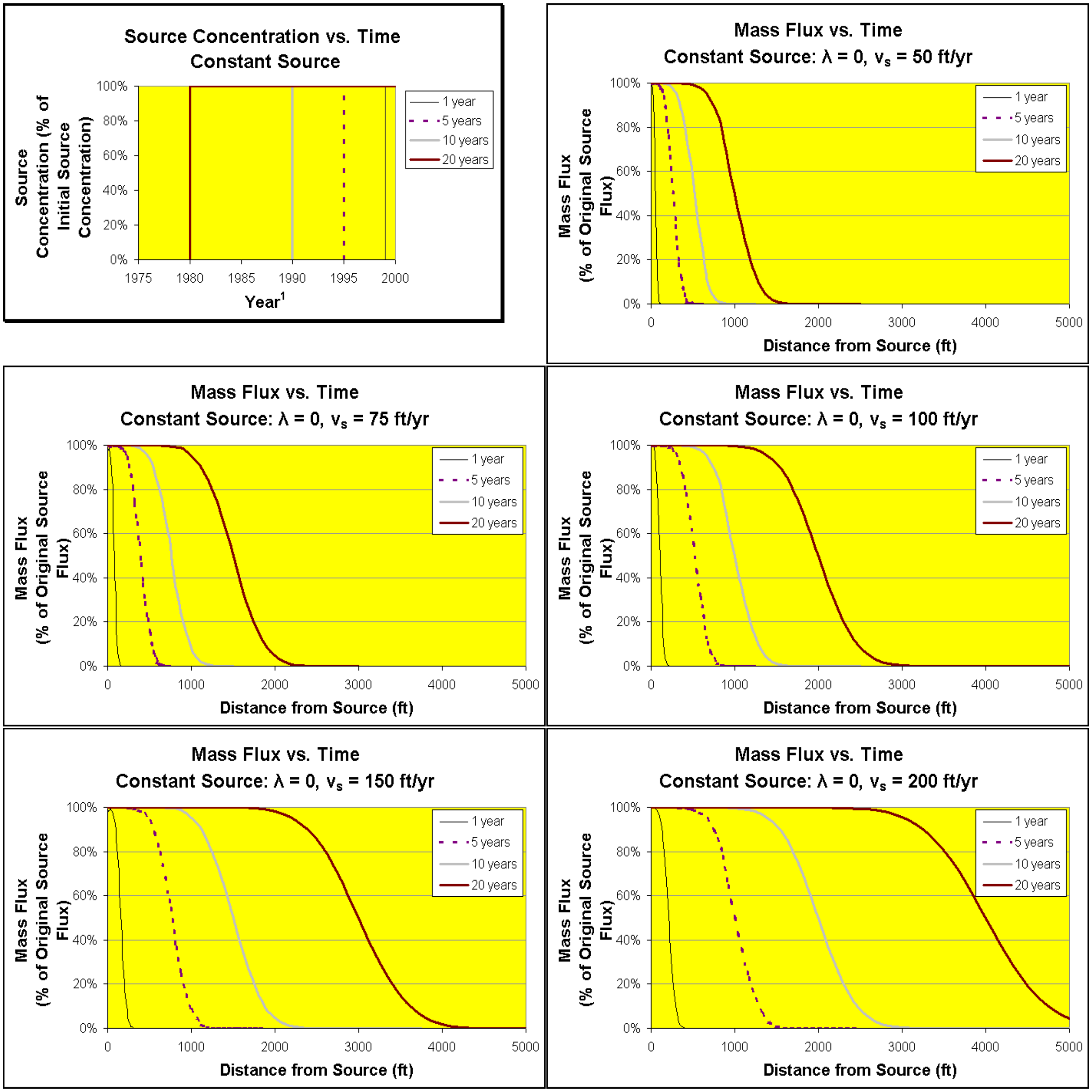
INDEX TO CONSTANT SOURCE MASS FLUX VS. DISTANCE CURVES

Source Type	Source Halflife ($t_{source\ half\text{-}life}$, yrs)	Seepage Velocity (ft/yr)	Plume Biodegradation Rate (per year)	Page Number
Decaying Source	1	50	No biodegradation (λ = 0)	A-7
	1	75	No biodegradation (λ = 0)	A-7
	1	100	No biodegradation (λ = 0)	A-7
	1	150	No biodegradation (λ = 0)	A-7
	1	200	No biodegradation (λ = 0)	A-7
Decaying Source	1	50	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	75	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	100	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	150	Moderate biodegradation (λ = 0.693/yr)	A-8
	1	200	Moderate biodegradation (λ = 0.693/yr)	A-8
Decaying Source	5	50	No biodegradation (λ = 0)	A-9
	5	75	No biodegradation (λ = 0)	A-9
	5	100	No biodegradation (λ = 0)	A-9
	5	150	No biodegradation (λ = 0)	A-9
	5	200	No biodegradation (λ = 0)	A-9
Decaying Source	5	50	Moderate biodegradation (λ = 0.693/yr)	A-10
	5	75	Moderate biodegradation (λ = 0.693/yr)	A-10
	5	100	Moderate biodegradation (λ = 0.693/yr)	A-10
	5	150	Moderate biodegradation (λ = 0.693/yr)	A-10
	5	200	Moderate biodegradation (λ = 0.693/yr)	A-10
Decaying Source	10	50	No biodegradation (λ = 0)	A-11
	10	75	No biodegradation (λ = 0)	A-11
	10	100	No biodegradation (λ = 0)	A-11
	10	150	No biodegradation (λ = 0)	A-11
	10	200	No biodegradation (λ = 0)	A-11
Decaying Source	10	50	Moderate biodegradation (λ = 0.693/yr)	A-12
	10	75	Moderate biodegradation (λ = 0.693/yr)	A-12
	10	100	Moderate biodegradation (λ = 0.693/yr)	A-12
	10	150	Moderate biodegradation (λ = 0.693/yr)	A-12
	10	200	Moderate biodegradation (λ = 0.693/yr)	A-12

SOURCE TYPE	Seepage Velocity (ft/yr)	Plume Biodegradation Rate (per year)	Page Number
Step Change (Full Strength for 1 year, then 90% strength)	50	No biodegradation (λ = 0)	A-13
	75	No biodegradation (λ = 0)	A-13
	100	No biodegradation (λ = 0)	A-13
	150	No biodegradation (λ = 0)	A-13
	200	No biodegradation (λ = 0)	A-13
Step Change (Full Strength for 5 years, then 10% strength)	50	No biodegradation (λ = 0)	A-14
	75	No biodegradation (λ = 0)	A-14
	100	No biodegradation (λ = 0)	A-14
	150	No biodegradation (λ = 0)	A-14
	200	No biodegradation (λ = 0)	A-14

MODELED MASS FLUX OF MTBE

Constant Source: λ = 0

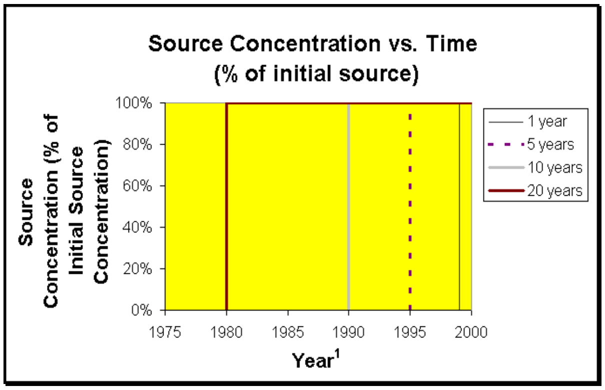


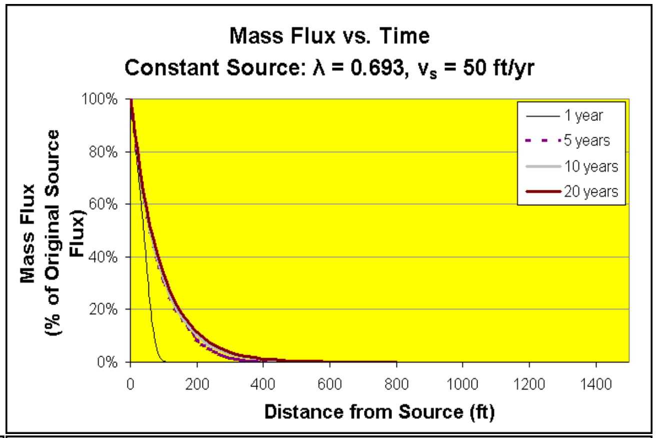
Notes:

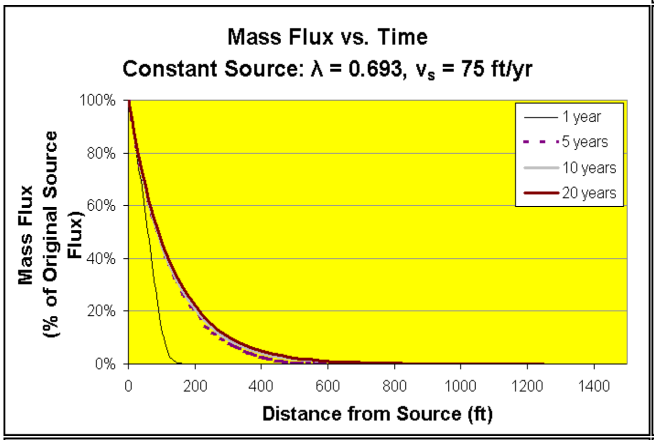
1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x / α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that $k_s < ((1+v_s/4\ \alpha_x)/R)$ to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = 0.693/t_{half}.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

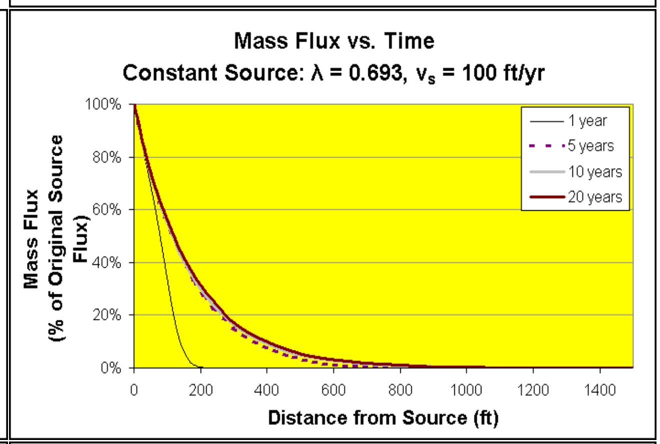
MODELED MASS FLUX OF MTBE

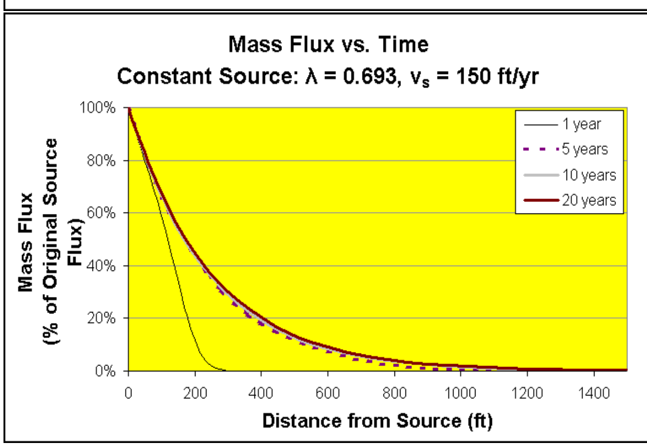
Constant Source: λ = 0.693

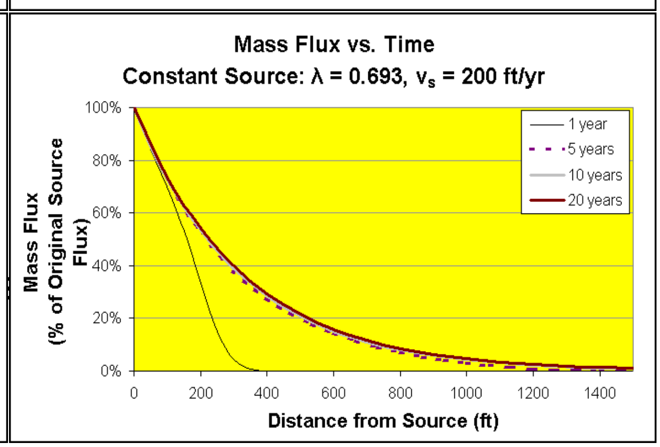










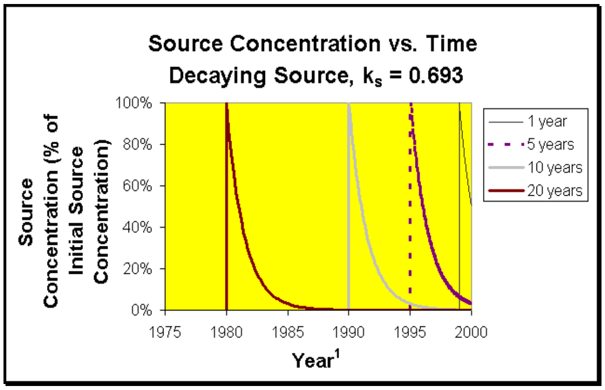


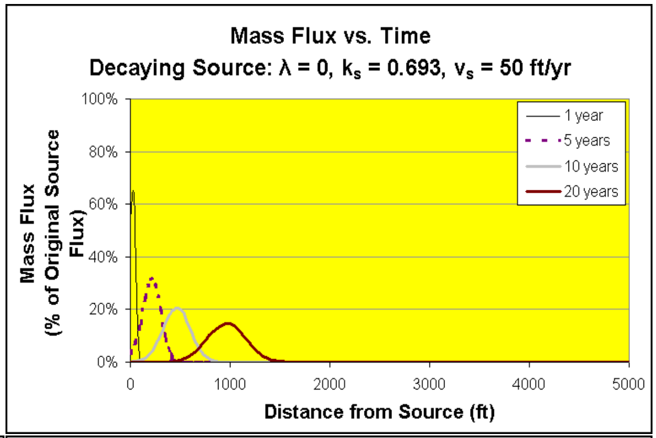
Notes:

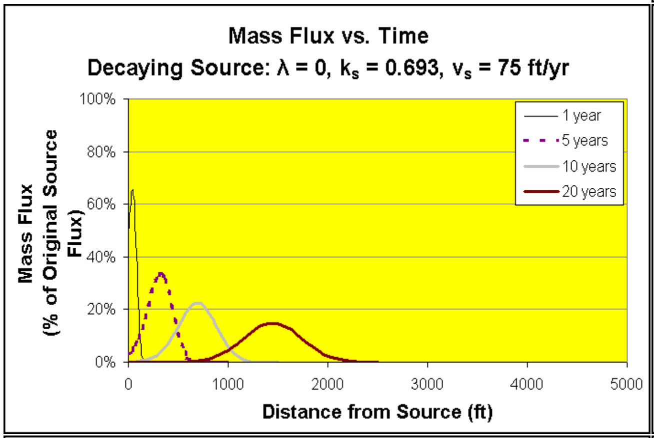
1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x / α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that $k_s < ((1+v_s/4\ \alpha_x)/R)$ to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = $0.693/t_{half}$.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

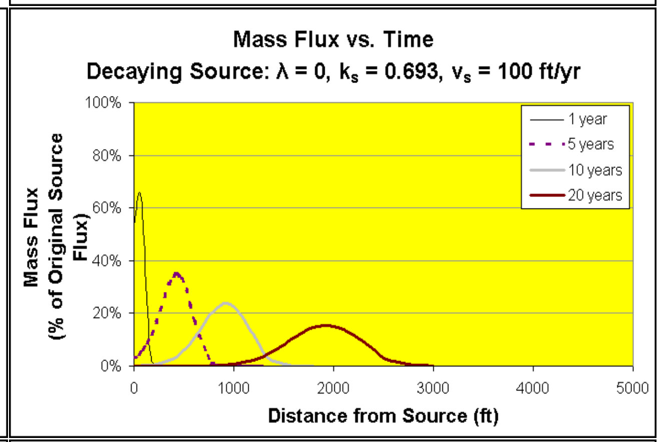
MODELED MASS FLUX OF MTBE

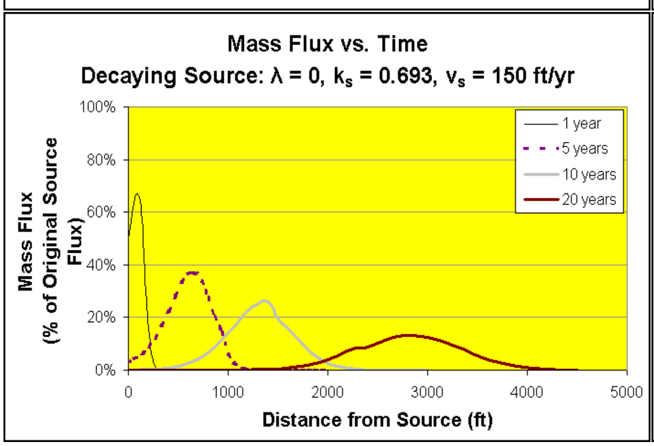
Decaying Source: λ = 0, $t_{source\ half}$ = 1 year

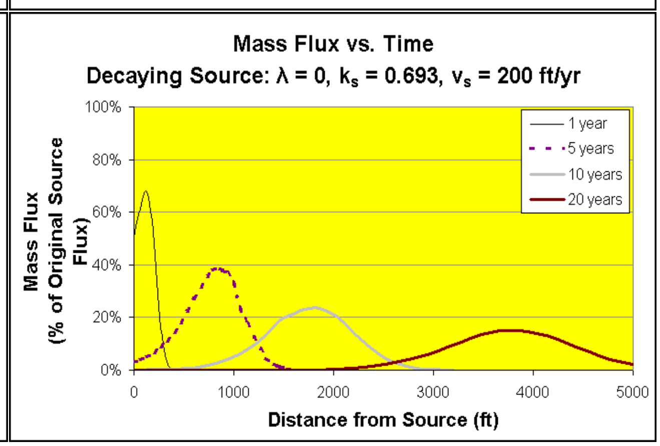










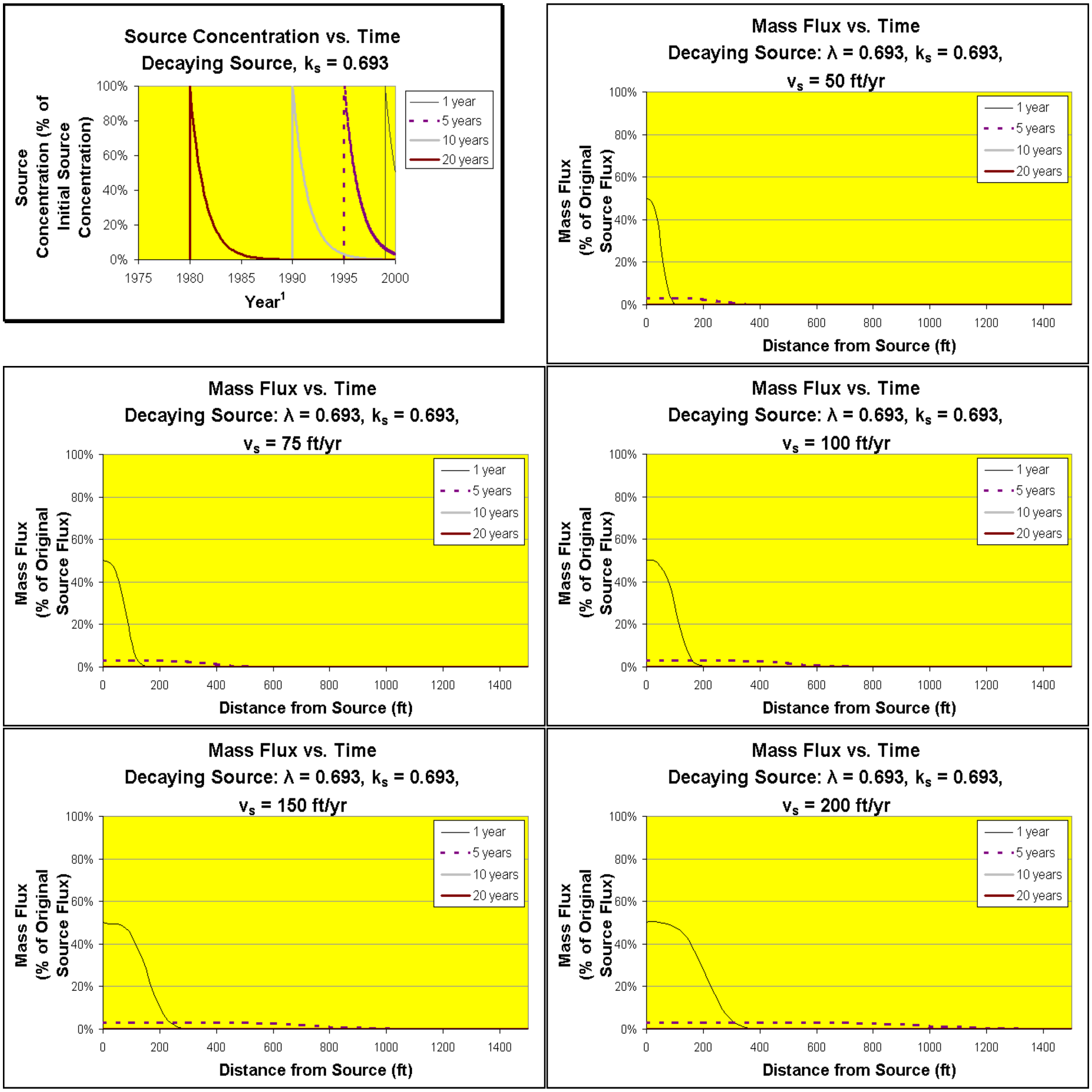


Notes:

1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x / α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that $k_s < ((1+v_s/4\ \alpha_x)/R)$ to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = $0.693/t_{half}$.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

MODELED MASS FLUX OF MTBE

Decaying Source: λ = 0.693, $t_{source\ half}$ = 1 year

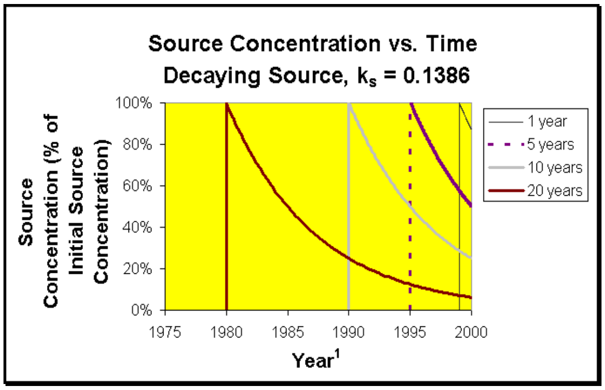


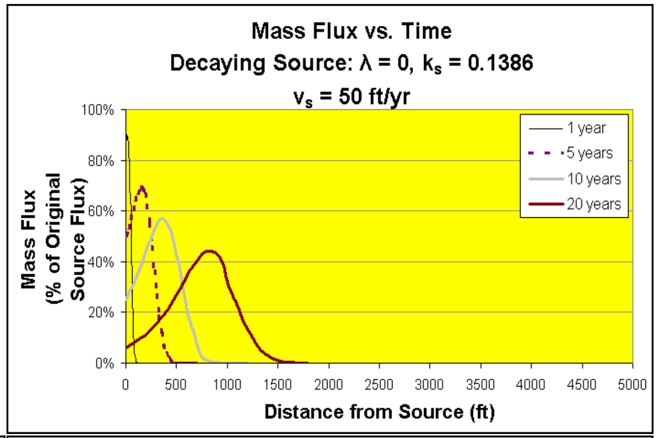
Notes:

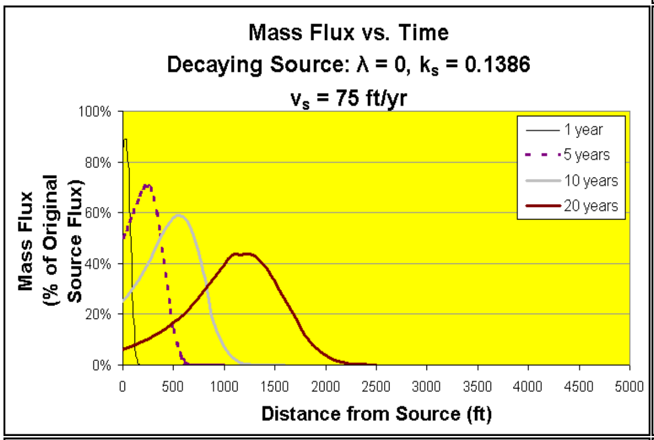
1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x/ α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that k_s < ((1+v_s/4 α_x)/R) to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = 0.693/t_{half}.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

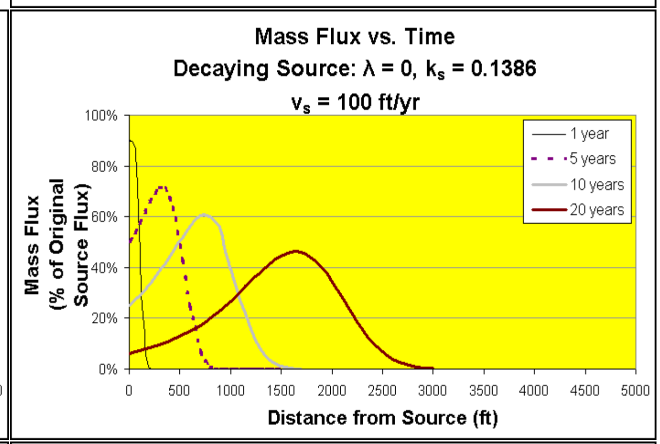
MODELED MASS FLUX OF MTBE

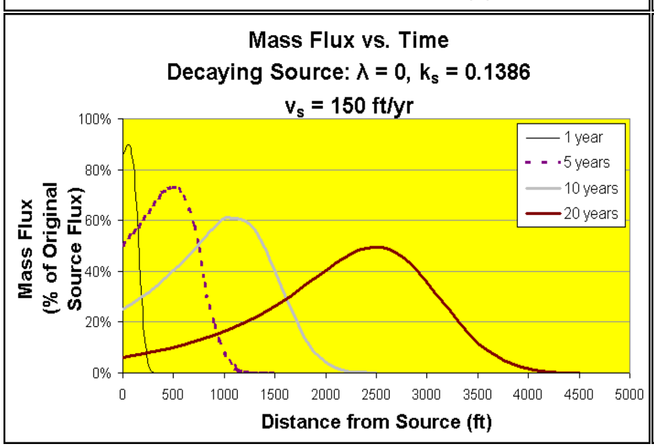
Decaying Source: $\lambda = 0$, $t_{source\ half} = 5$ years

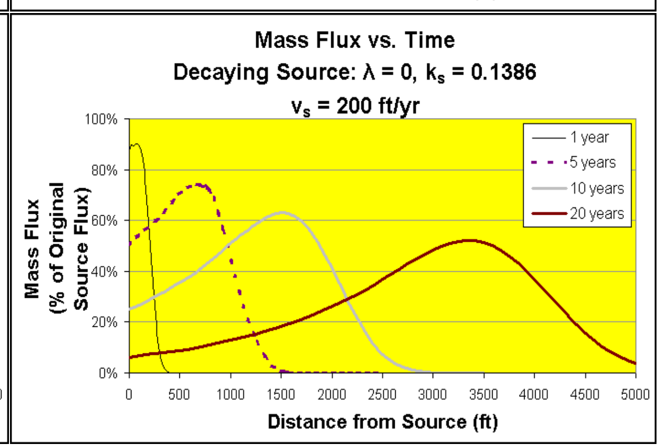










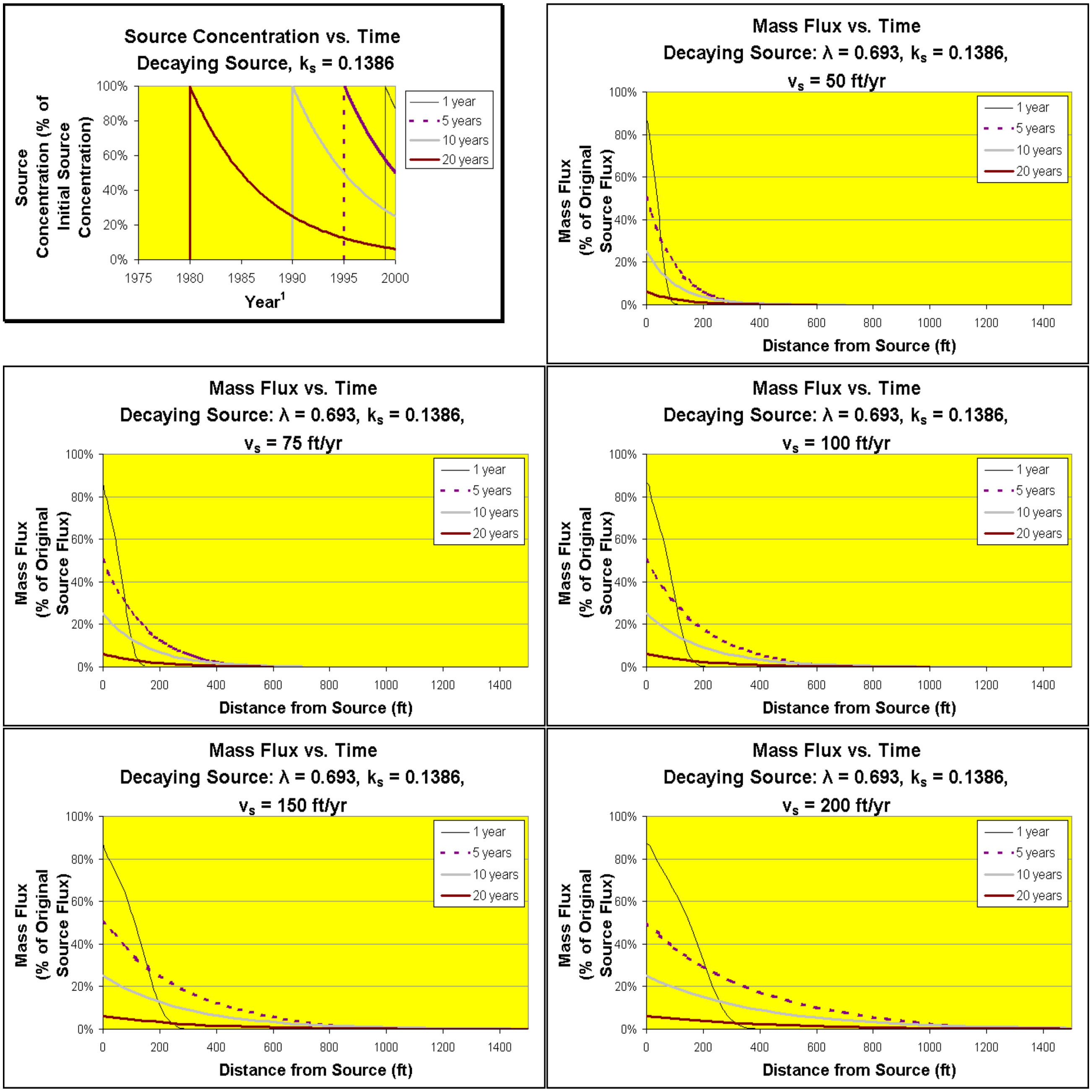


Notes:

1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, $\alpha_x / \alpha_y = 0.1$, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that $k_s < ((1+v_s/4\ \alpha_x)/R)$ to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = $0.693/t_{half}$.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

MODELED MASS FLUX OF MTBE

Decaying Source: λ = 0.693, $t_{source\ half}$ = 5 years

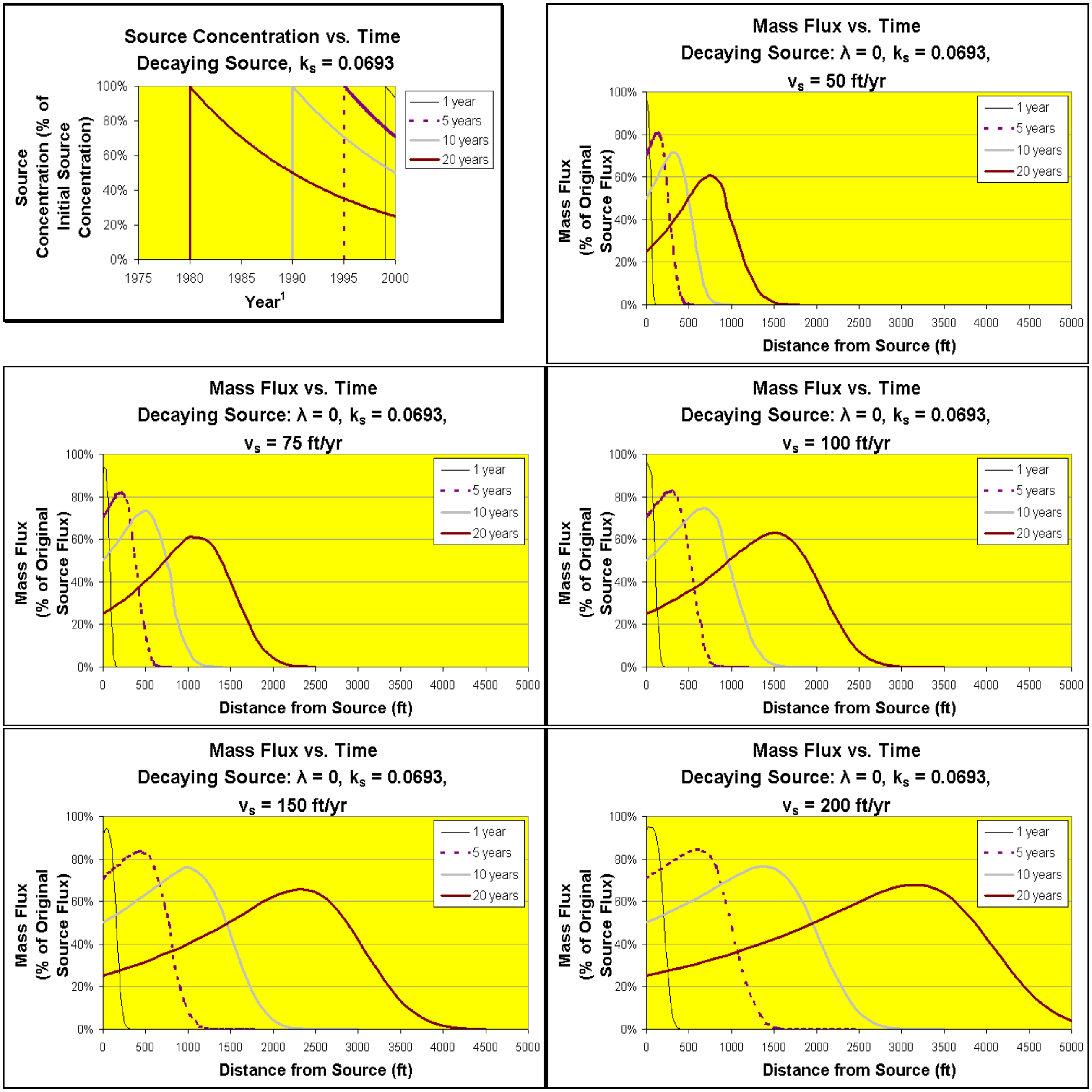


Notes:

1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x / α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that k_s < ((1+v_s/4 α_x)/R) to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = 0.693/t_{half}.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

MODELED MASS FLUX OF MTBE

Decaying Source: λ = 0, $t_{source\ half}$ = 10 years

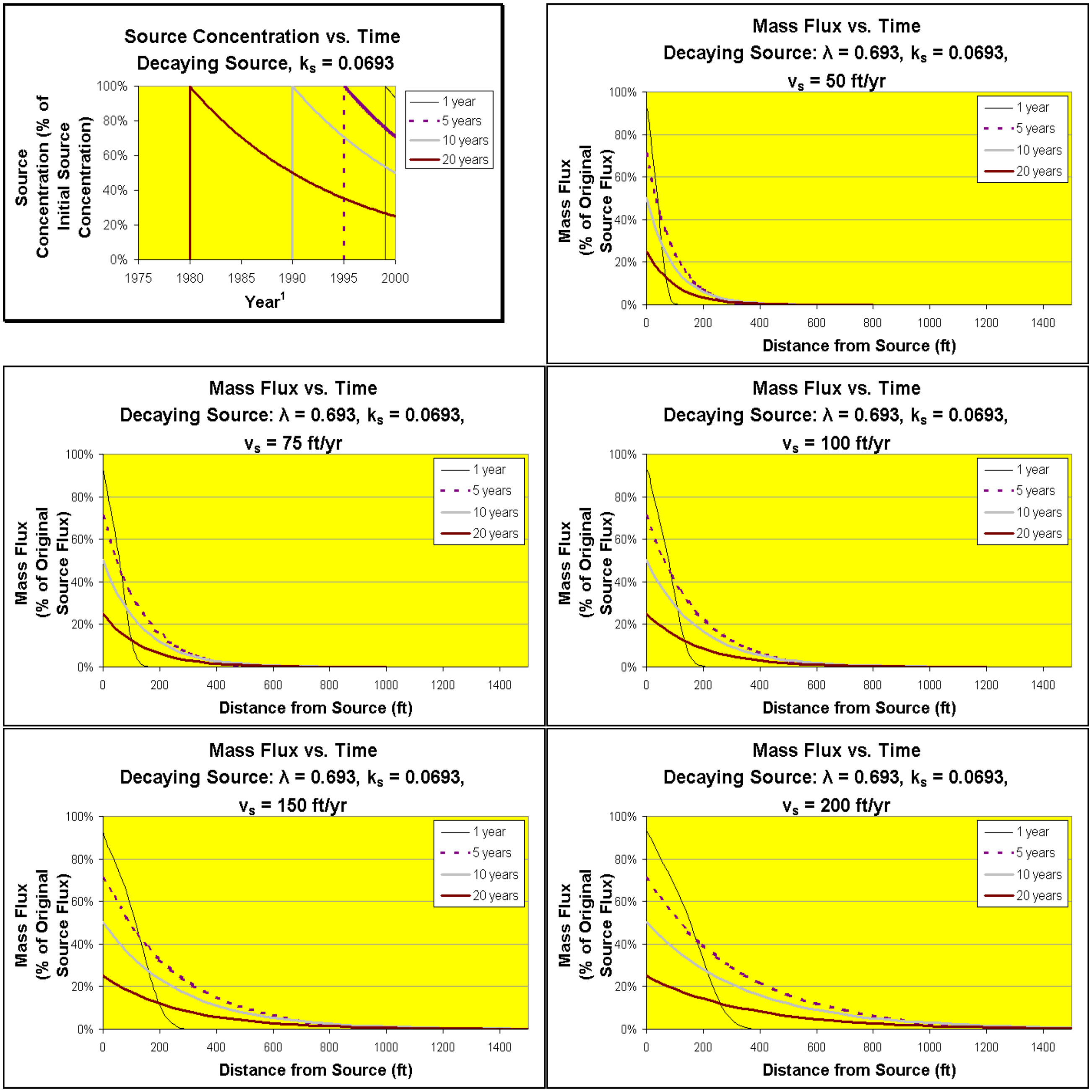


Notes:

1. Year 2000 modeled as current year. Add number of years since then to x-axis values of source graph.
2. Mass Flux calculations based on a Domenico model with first order biotransformation and source decay. Flux calculated numerically with a 30 x 30 spatial grid.
3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x/ α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that k_s < ((1+v_s/4 α_x)/R) to prevent a negative square root in the Domenico model equation.
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = 0.693/t_{half}.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

MODELED MASS FLUX OF MTBE

Decaying Source: λ = 0.693, $t_{source\ half}$ = 10 years



Notes:

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3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
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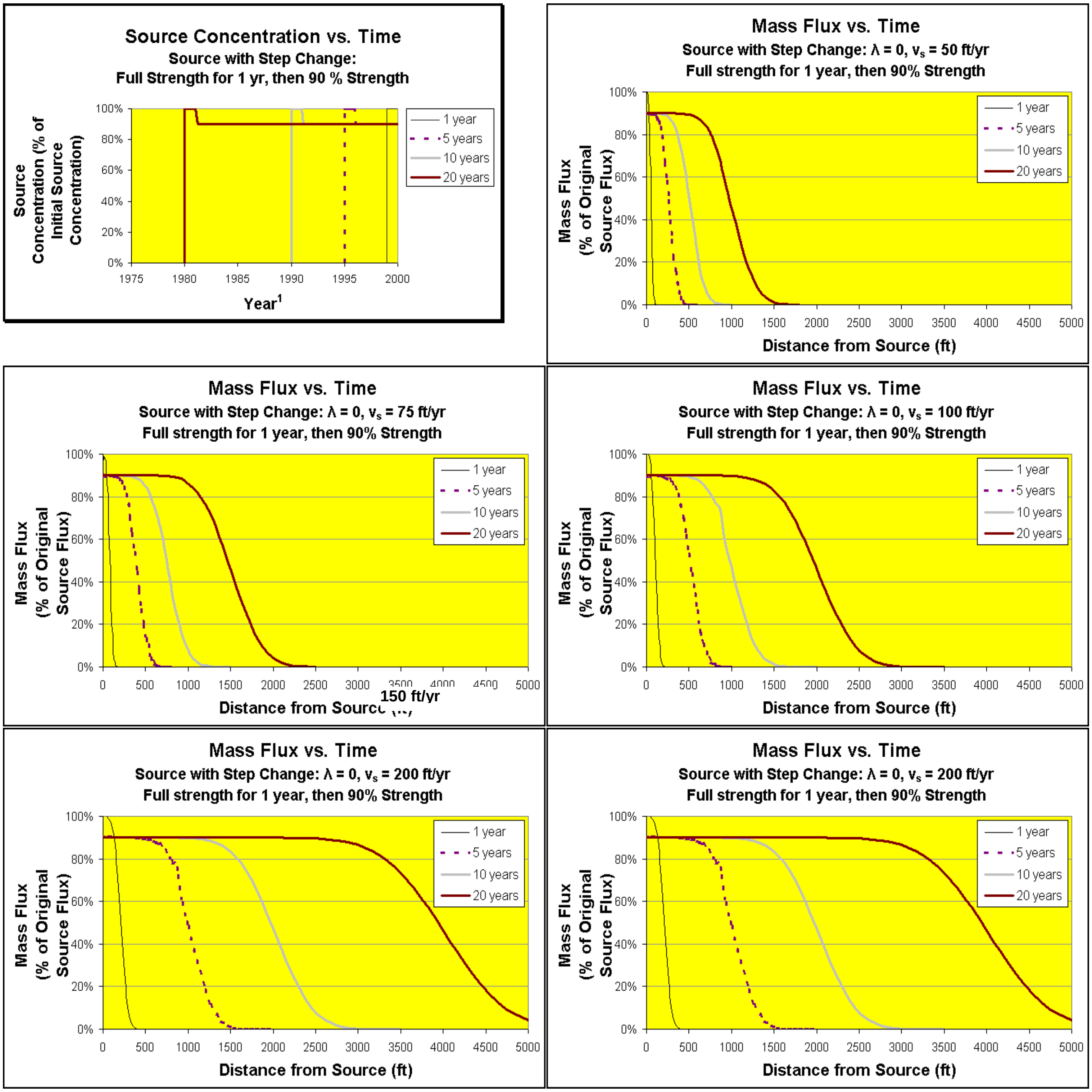
5. Parameters Varied: v_s = seepage velocity, λ = first order degradation rate, k_s = source decay constant = 0.693/t_{half}.
6. Modeled plume widths for 5, 10, and 20 year sources were adjusted for different values of v_s to ensure a close fit. For v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr, modeled widths were 6, 8, 10, 12, and 15 times source zone width respectively. For the 1 year source, modeled widths for v_s = 50 ft/yr, 75 ft/yr, 100 ft/yr, 150 ft/yr, and 200 ft/yr were 3, 4, 5, 6, and 7.5 times source zone width, respectively.

MODELED MASS FLUX OF MTBE

Step-Function Source: λ = 0, Full Strength for 1 year, then 90% Strength



Notes:

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3. Concentrations < 0.02 mg/L omitted from calculations based on drinking water limit of 20 - 40 ug/L.
4. Parameters assumed: Retardation factor = 1, Initial Concentration = 100 mg/L, α_x / α_y = 0.1, n = 0.2. α_x calculated using Modified Xu and Eckstein: α_x = 0.82*3.28*(LOG(v_s*time/3.28))^2.446, except when reduced so that $k_s < ((1+v_s/4\ \alpha_x)/R)$ to prevent a negative square root in the Domenico model equation.
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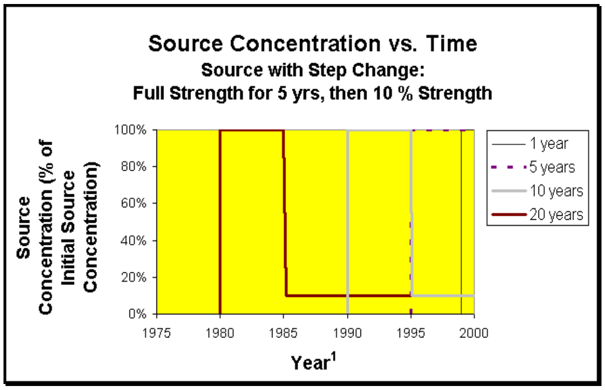
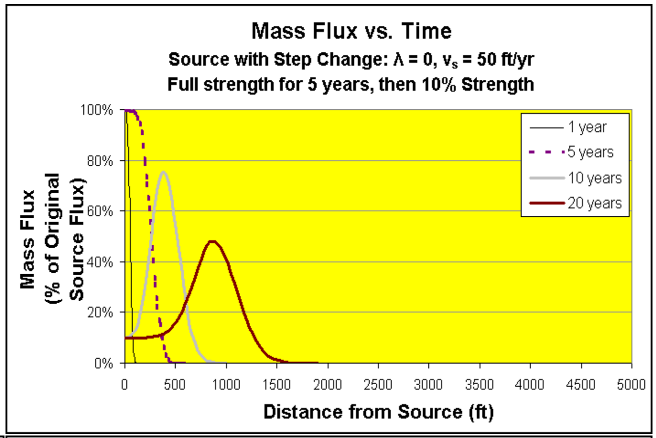
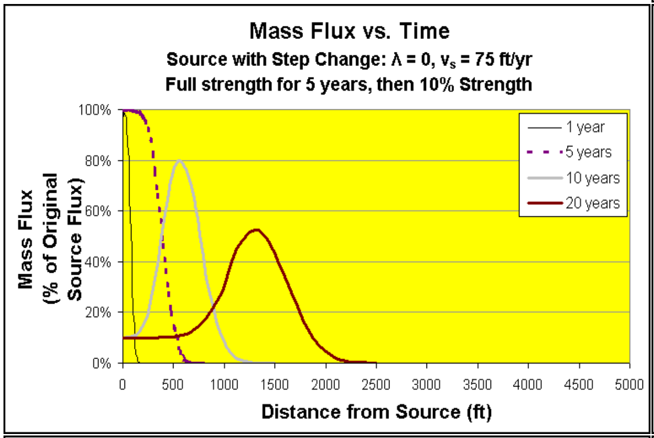
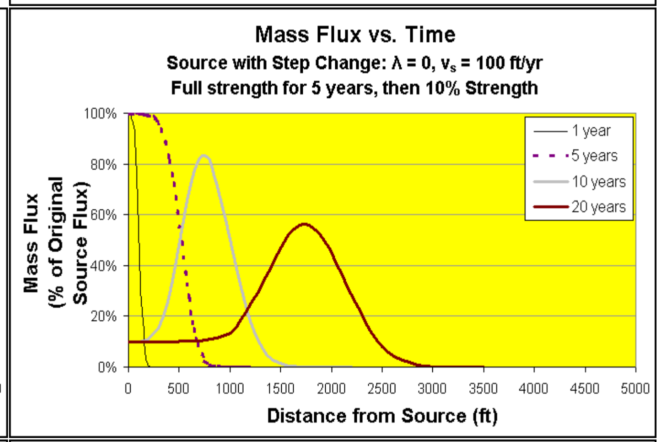
MODELED MASS FLUX OF MTBE

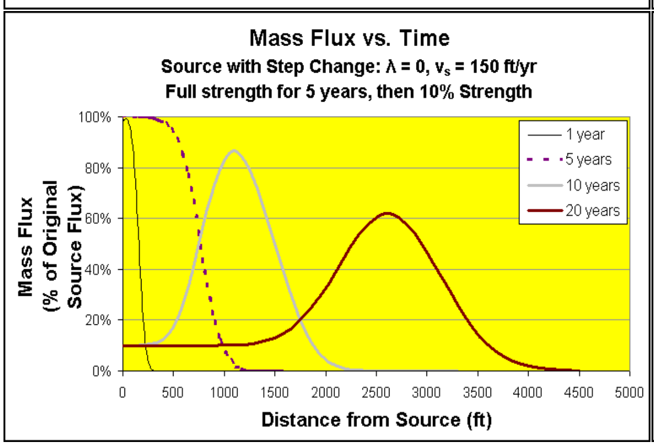
Step-Function Source: λ = 0, Full Strength for 5 years, then 10% Strength

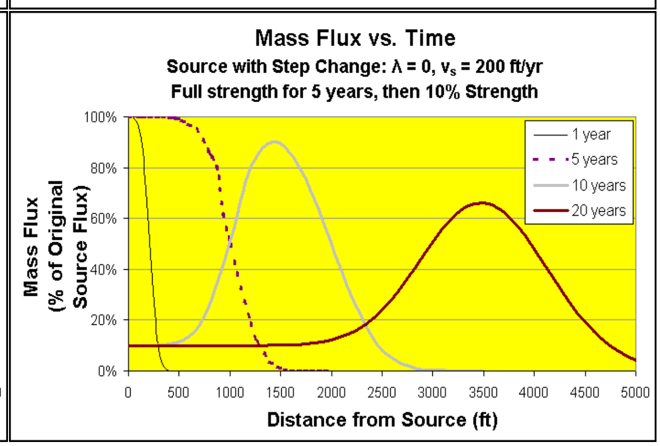












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APPENDIX B – EXAMPLES

Groundwater Remediation Strategies Tool
American Petroleum Institute

EXAMPLE 1: BASELINE MTBE MASS FLUX

Problem:

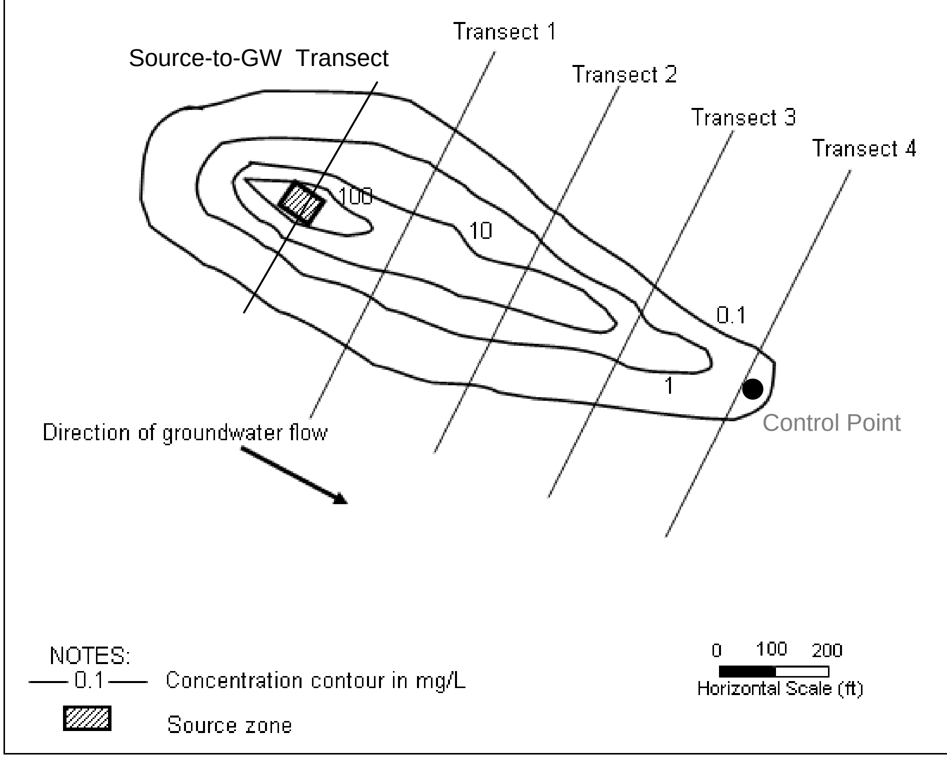
Determine the MTBE concentration at a control point with a 10 gpm (54,504 L/day) water supply well located at the edge of an MTBE plume.

The vadose zone has an average MTBE concentration of 4.2 mg/kg. The source zone is 65 ft (1981 cm) long in the direction parallel to groundwater flow and 50 ft (1524 cm) long in the direction perpendicular to groundwater flow. The top 3 ft (91 cm) of the soil is contaminated and is underlain by 2 ft (61 cm) of clean unsaturated soils before reaching the water table. The plume is 1000 ft long.

Assume a log K_{oc} value for MTBE is 1.08; and Henry's law constant for MTBE is 0.024 cm^3 H_2O/cm^3 air

The hydraulic conductivity is 0.032 cm/sec; hydraulic gradient is 0.002 cm/cm, and saturated zone porosity is 0.30, giving a groundwater seepage velocity of 221 ft/yr. In the vadose zone, the measured f_{oc} of the soil is 0.006, 100 cm of annual precipitation, a soil bulk density of 1.7 g/mL, volumetric water content = 0.08 cm^3 H_2O/cm^3 soil, and volumetric air content = 0.33 cm^3 air/cm^3 soil. The contaminated soils are clean, well-sorted sands.

A small 10-gpm (37.8 L/min) municipal well is located at the control point.



MTBE Transects Through 2-D Plume Contour Map

Solution

Step MFB-1. Calculate the Baseline Vadose Zone to Groundwater Mass Flux

First estimate the annual infiltration in the vadose zone. For sandy soils the infiltration is:
$I_f = 0.0018(100)^2 = 18$ cm/yr

The area of the contaminated soil zone is:
$A = (1981)(1524) = 3.02\text{x}10^6$ cm^2 .

Then estimate the vadose zone to groundwater mass flux:

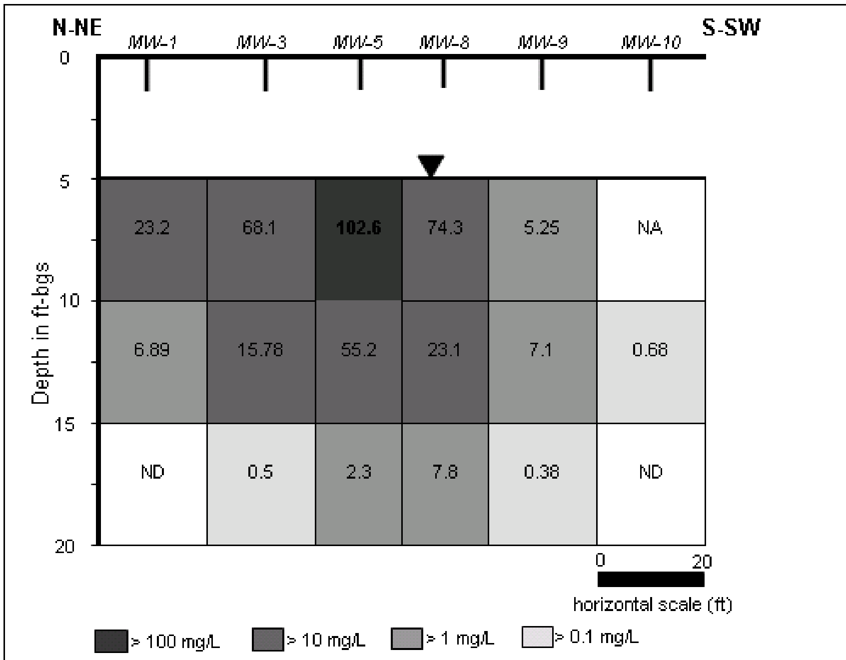
$$w\_b_{vd} = \left(\frac{4.2}{(0.08/1.7) + 0.006\left(10^{1.08}\right) + 0.024(0.33/1.7)} \left(\frac{91}{91+61} \right) \right) (18)\left(3.02\times10^{6}\right)\left(2.74\times10^{-9}\right)$$

The vadose zone mass flux to groundwater is:
$w\_b_{vd} = 3.0$ g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

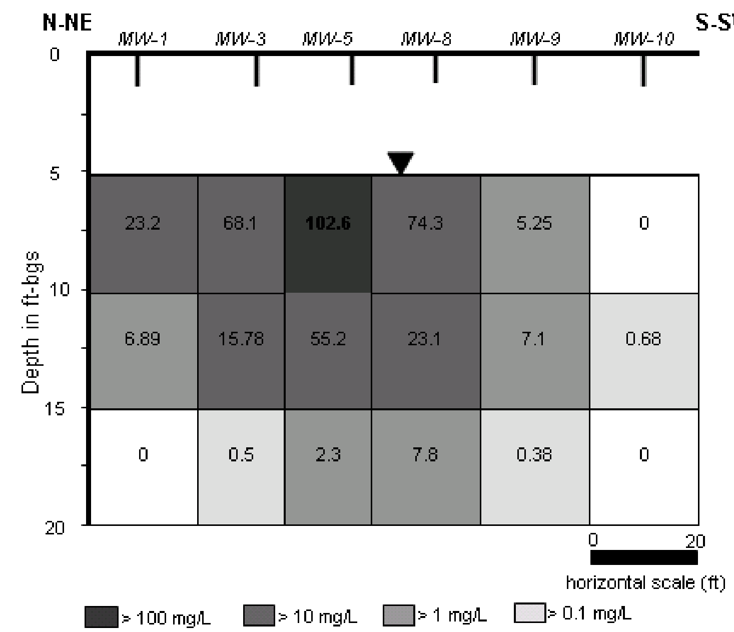
Step MFB-2. Calculate the Baseline Total Source to Groundwater Mass Flux

First, divide the vertical cross-section of the plume into different flow areas.



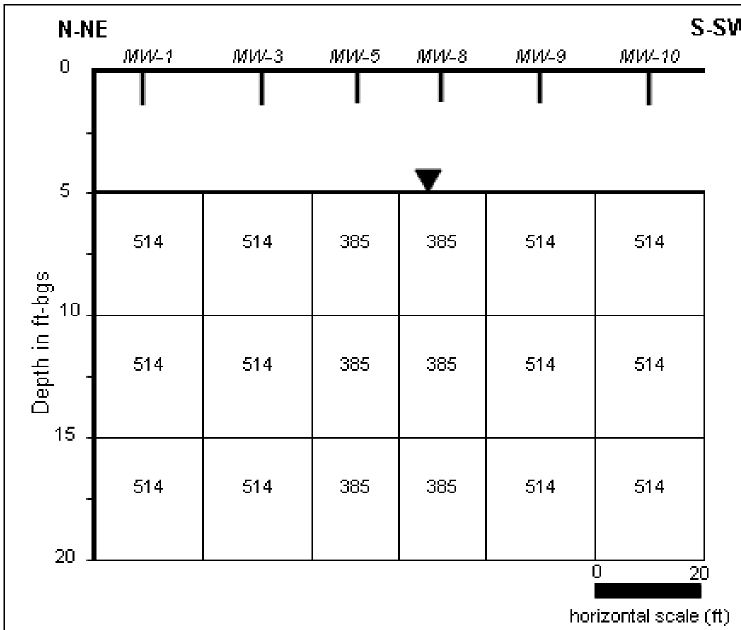
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next assign values to all non-detects (ND) and not analyzed (NA) samples:



MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-Section of Plume

Then estimate the discharge (L/day) through each flow area. For example:



Discharge Through Each Flow Area (L/day)

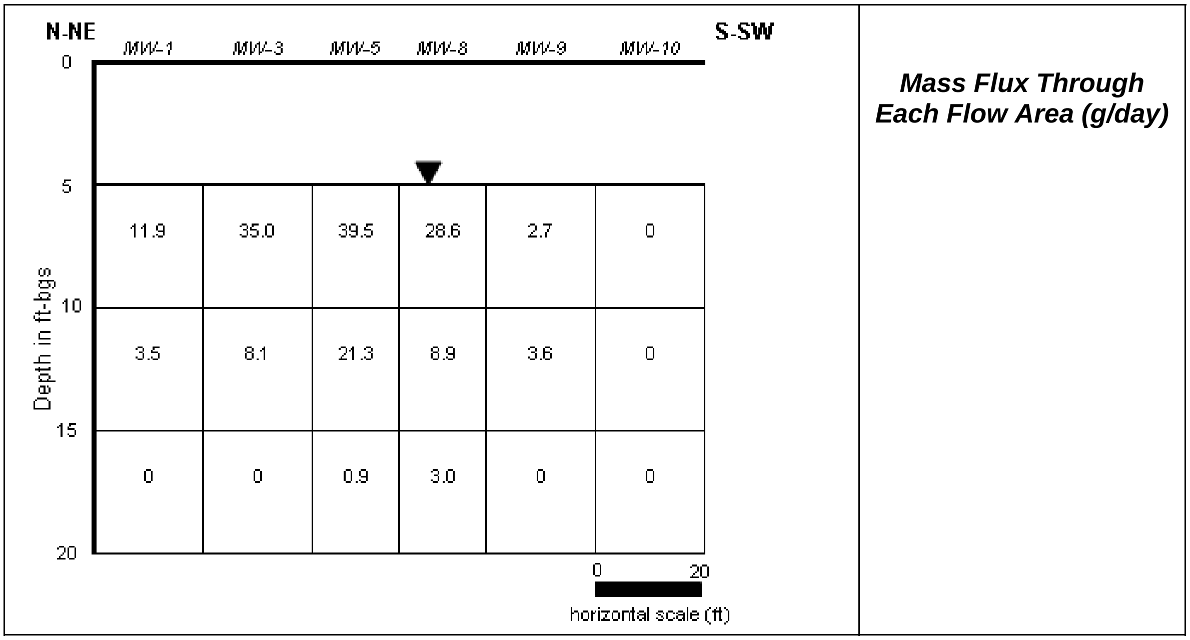
For example, for flow area 1,1 (the top left flow area)::

$q_{1,1}$ = (0.032 cm/sec)(0.002 cm/cm)(5 ft x 20 ft)(30.5^2 cm^2/ft^2) (L/1000 cm^3) (86,400 sec/day)

$q_{1,1}$ = (0.032 cm/sec)(0.002 cm/cm)(5 ft x 20 ft)(80,374 $Lday^{-1}/cm\text{-}ft^2sec^{-1}$)

$q_{1,1}$ = 514 L/day

Next calculate the mass flux (g/day) associated with each flow area (using a conversion factor of 1000 mg/g). For example:



For example, the mass flux through flow area 1,2 is:
$w\_b_{1,2}$ = (68 mg/L)(514 L/day) /(1000 mg/g)
$w\_b_{1,2}$ = 35.0 g/day

Finally, sum the mass fluxes for all the wells to get the total mass flux:
$w\_b_{ts} = \sum_{i=1}^{i=n} C_i \cdot q_i$
w_b_{ts} = 168 g/day

Groundwater total source mass flux is:
w_b_{ts} = 168 g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

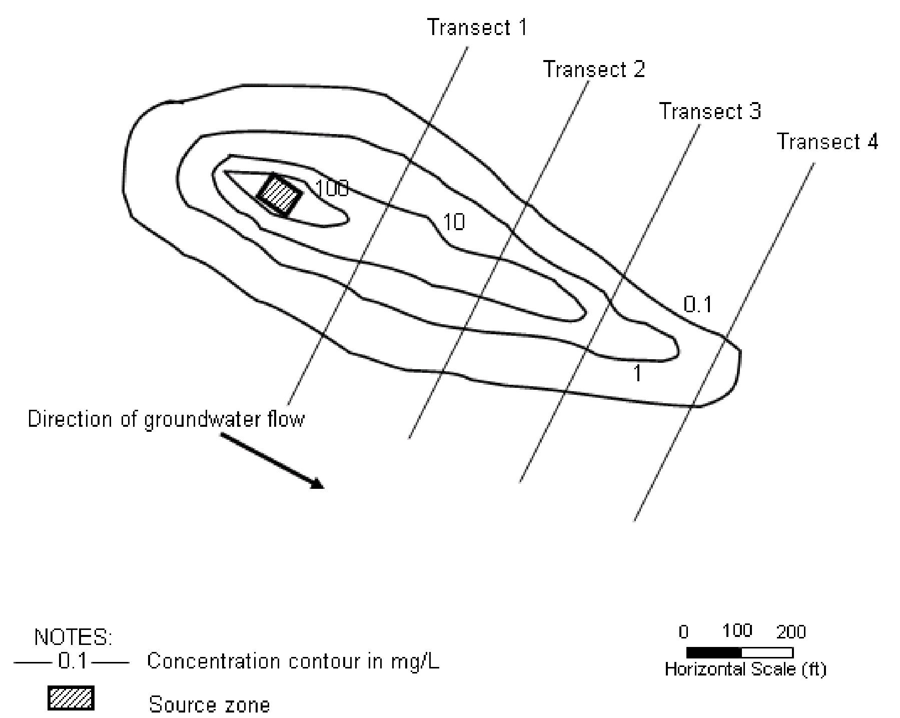
Step MFB-3. Calculate the Baseline Smear Zone to Groundwater Mass Flux

$w\_b_{sm} = w\_b_{ts} - w\_b_{vd}$
w_b_{sm} = 168 – 3.0 = 165 g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

Step MFB-4. Calculate the Transect Zone Mass Fluxes

First divide the plume into different transects perpendicular to the flow of groundwater:

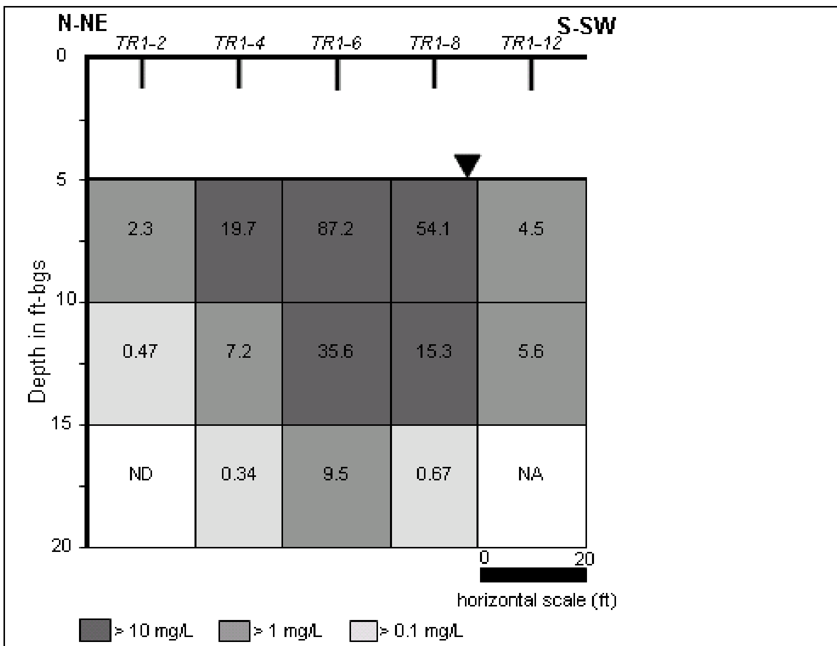


MTBE Transects Through 2-D Plume Contour Map

Next divide the vertical cross-section of the each transect into different downgradient flow areas.

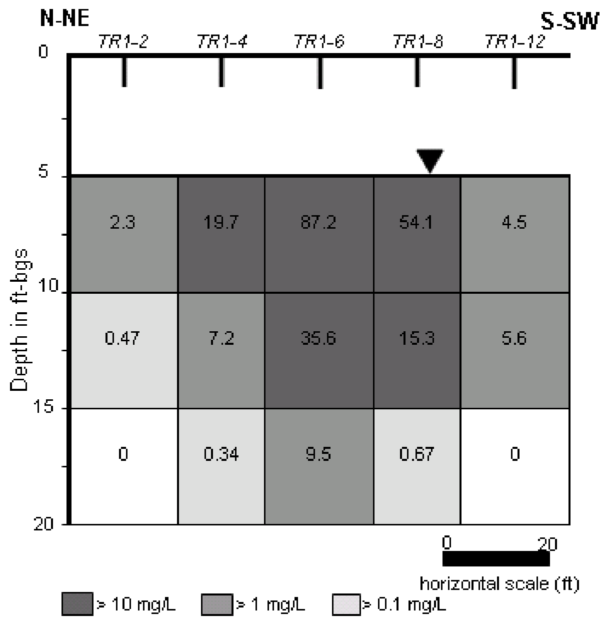
TRANSECT ZONE 1

First determine the MTBE concentrations (mg/L) and flow areas for vertical cross-section of Transect 1:



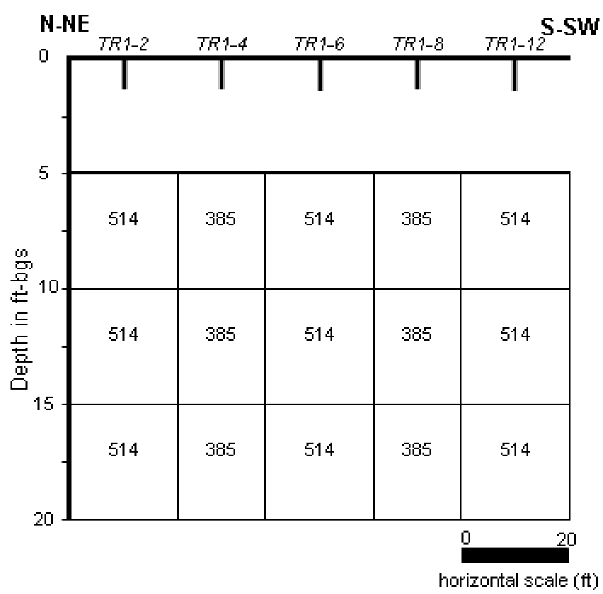
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next assign values to all non-detects and not analyzed samples:



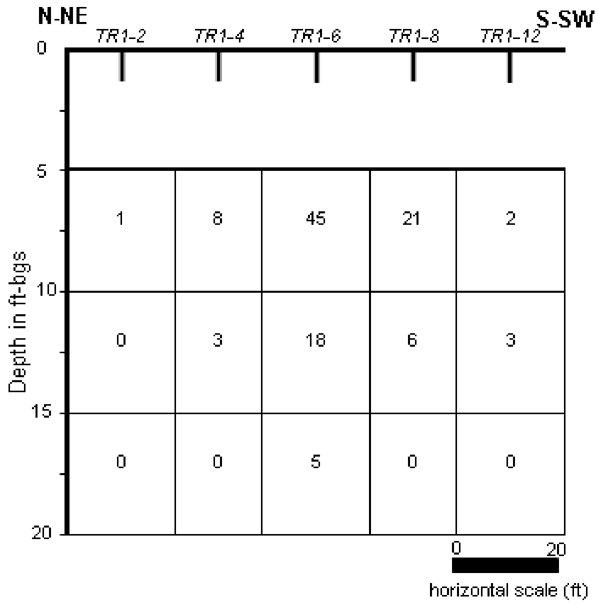
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next estimate the discharge (L/day) through each flow area:



Discharge Through Each Flow Area (L/day)

Then calculate the mass flux (g/day) associated with each flowarea:



Mass Flux Through Each Flow Area (g/day)

Finally, sum the mass fluxes for all the wells to get the total mass flux:

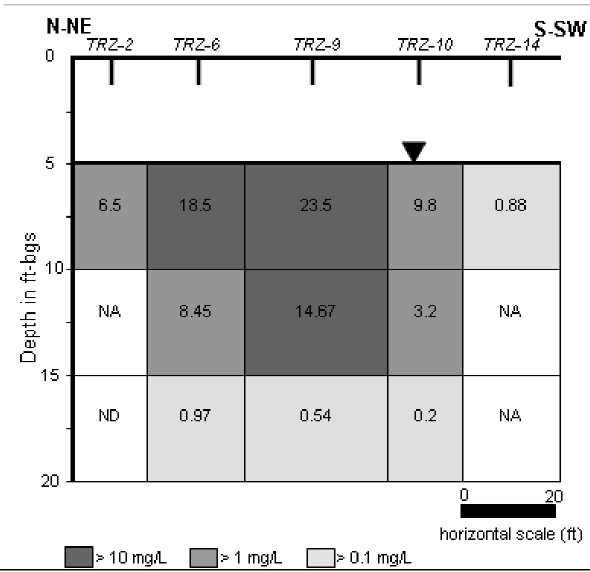
$w\_b_{gw} = \sum_{i=1}^{i=n} C_i \cdot q_i$ = 112 g/day

Total groundwater source mass flux through Transect 1 is:
$w\_b_{gw\text{-}1}$ = 112 g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

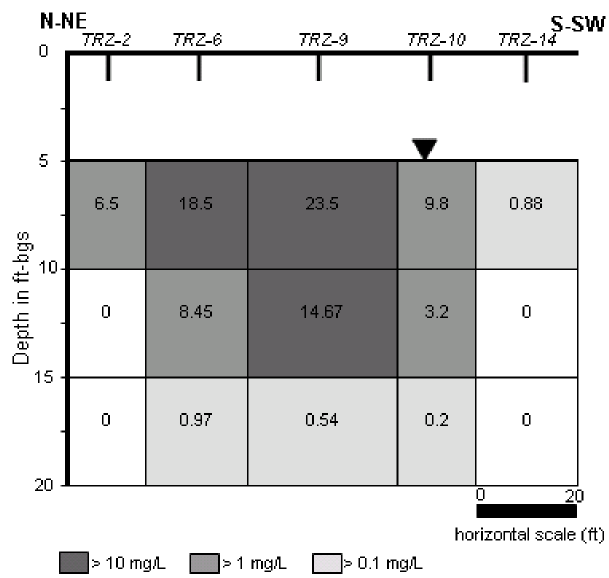
TRANSECT ZONE 2

First determine the MTBE concentrations (mg/L) and flow areas for vertical cross-section of Transect 2:



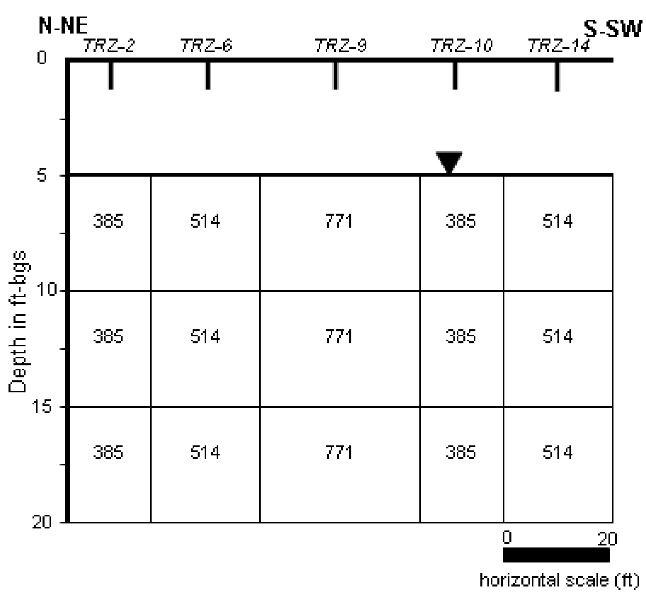
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross Section of Plume

Next assign values to all non-detects and not analyzed samples:



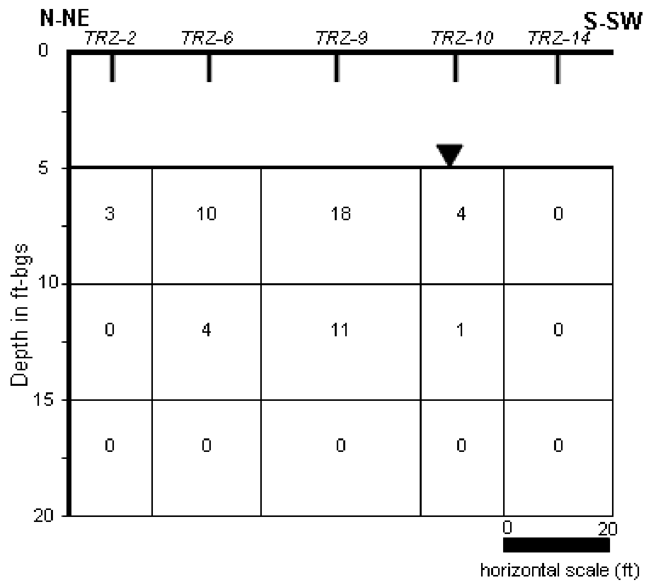
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next estimate the discharge (L/day) through each flow area:



Discharge Through Each Flow Area (L/day)

Then calculate the mass flux (g/day) associated with each flow area:



Mass Flux Through Each Flow Area (g/day)

Finally, sum the mass fluxes for all the wells to get the total mass flux:

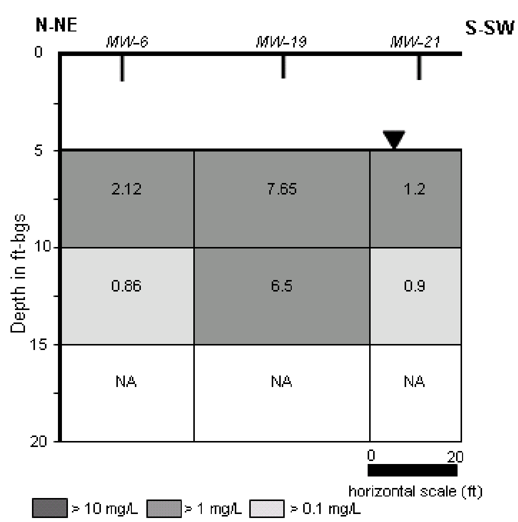
$w\_b_{gw} = \sum_{i=1}^{i=n} C_i \cdot q_i$ = 52 g/day

The total groundwater source mass flux through Transect 2 is:
$w\_b_{gw\text{-}2}$ = 52 g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

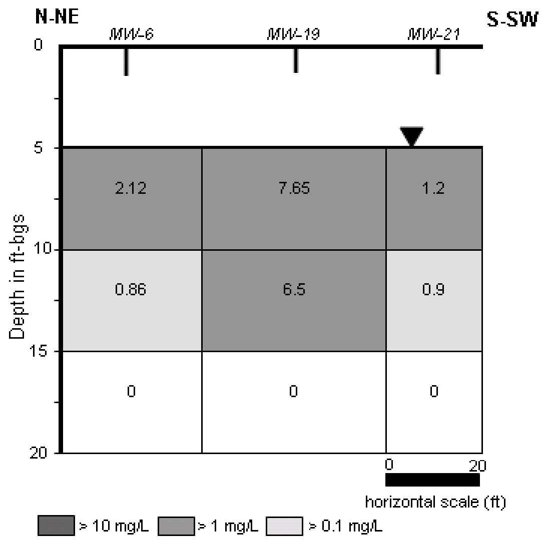
TRANSECT ZONE 3

First determine the MTBE concentrations (mg/L) and flow areas for vertical cross-section of Transect 3:



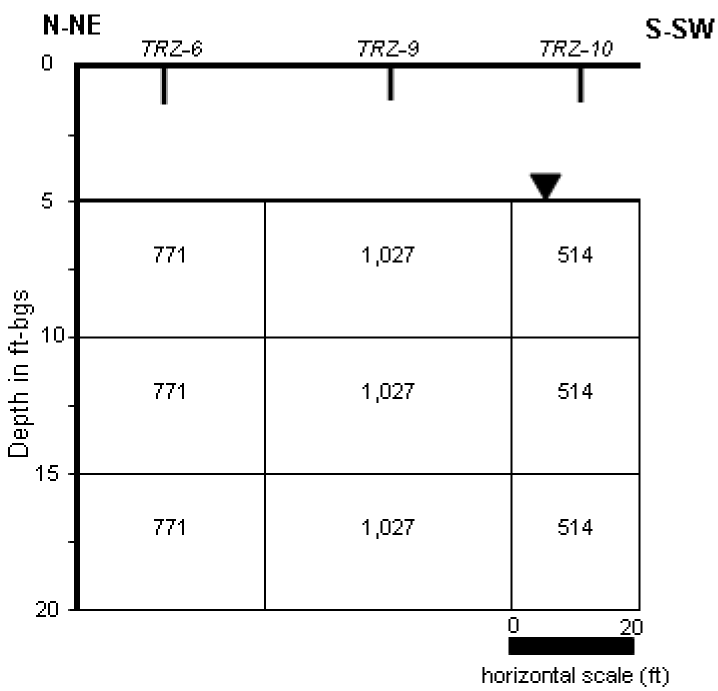
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next assign values to all non-detects and not analyzed samples:



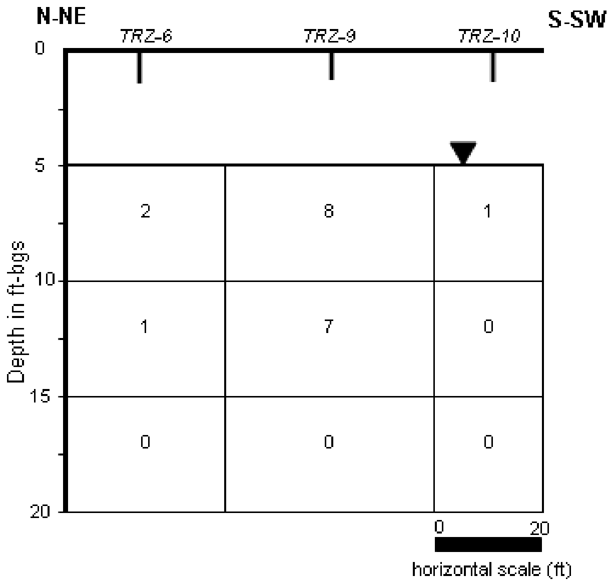
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next estimate the discharge (L/day) through each flow area:



Discharge Through Each Flow Area (L/day)

Then calculate the mass flux (g/day) associated with each flow area:



Mass Flux Through Each Flow Area (g/day)

Finally, sum the mass fluxes for all the wells to get the total mass flux:

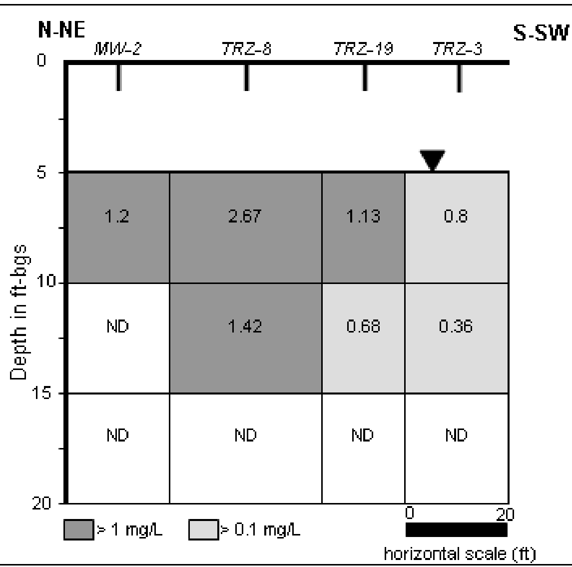
$w\_b_{gw} = \sum_{i=1}^{i=n} C_i \cdot q_i$ = 18 g/day

The total groundwater source mass flux through Transect 3 is:
$w\_b_{gw\text{-}3}$ = 18 g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

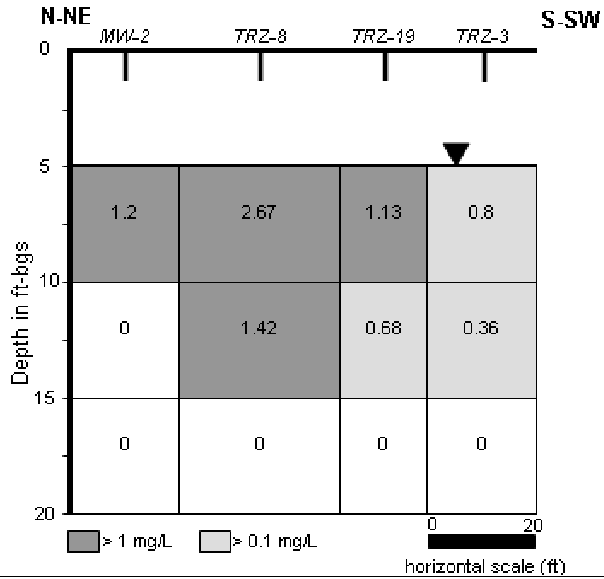
TRANSECT ZONE 4

First determine the MTBE concentrations (mg/L) and flow areas for vertical cross-section of Transect 4:



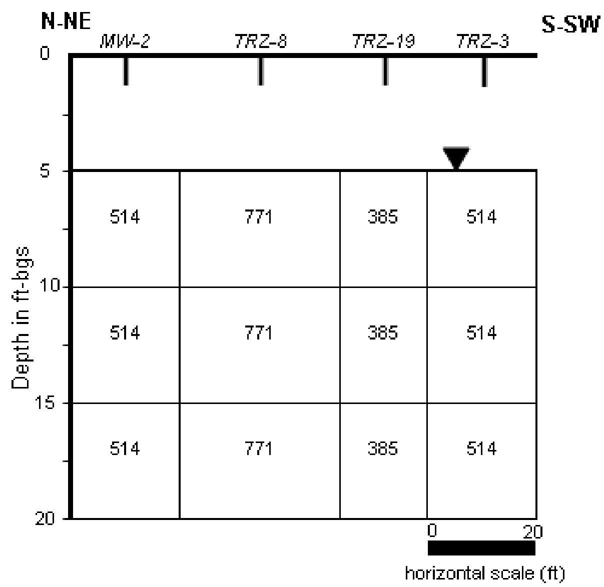
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next assign values to all non-detects and not analyzed samples:



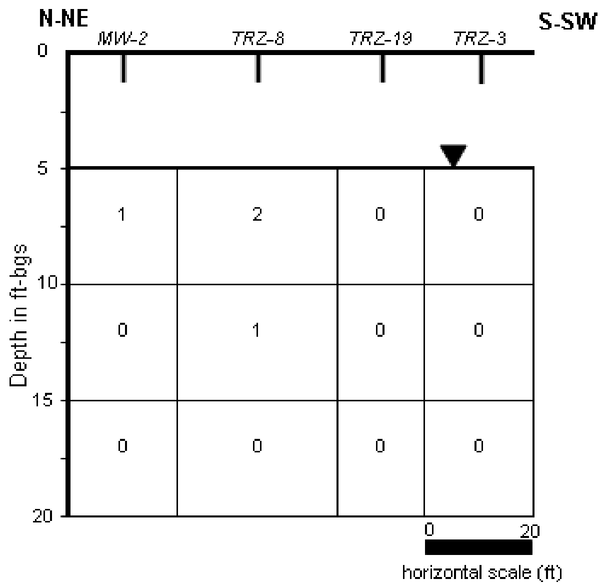
MTBE Concentrations (mg/L) and Flow Areas for Vertical Cross-section of Plume

Next estimate the discharge (L/day) through each flow area:



Discharge Through Each Flow Area (L/day)

Then calculate the mass flux (g/day) associated with each flow area:



Mass Flux Through Each Flowarea (g/day)

Finally, sum the mass fluxes for all the wells to get the total mass flux:

$w\_b_{gw} = \sum_{i=1}^{i=n} C_i \cdot q_i$ = 5.1 g/day

The total groundwater source mass flux through Transect 4 is:
w_b_{gw-4} = 5.1 g/day

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

Step MFB-5. Calculate the Baseline Control Point Concentration

w_{gw-n} = 5.1 g/day = 5,100 mg/day
Q_{cp} = 10 gpm = 54,504 L/day

The baseline control point MTBE concentration is:
C_b_{cp} = 5,100/54,504 = 0.094 mg/L

Enter this value on Worksheet 1, BASELINE MASS FLUX AND REMEDIATION TIMEFRAME TOOL.

SUMMARY - EXAMPLE 1: BASELINE MTBE MASS FLUX

The mass flux of MTBE ranges from 168 g/day at the point leaving the source zone to 5.1 g/day at the control point (a small municipal well).

The estimated baseline MTBE concentration at the control point is 0.094 mg/L. This value assumes the plume is at a steady-state condition. Some corrective action measures may be required to reduce the control point concentration. Use Worksheet 2 to evaluate the impact of different remediation alternatives.

Step RTB-1. **Calculate the Vadose Zone Natural Attenuation Timeframe**

Based on engineering judgement, the time required to naturally attenuate the MTBE in the vadose zone soils is 20 years.

Step RTB-2. **Calculate the Smear Zone Natural Attenuation Timeframe**

Based on a simple mass balance model, the time required to naturally attenuate the MTBE in the smear zone is 40 years.

Step RTB-3. **Calculate the Total Source Natural Attenuation Timeframe**

The total source remediation timeframe is the longer of Step RTB-1 and RTB-2. In this case, the total source remediation timeframe is 40 years.

Step RTB-4. **Calculate the Groundwater Transect Zone Natural Attenuation Timeframe**

Estimate the travel time from the source to each transect:

TRANSECT 1: Distance ÷ (Seepage velocity x retardation factor)
132 ft ÷ (221 ft/yr x 1.0) = 0.6 yrs

TRANSECT 2: Distance ÷ (Seepage velocity x retardation factor)
338 ft ÷ (221 ft/yr x 1.0) = 1.5 yrs

TRANSECT 3: Distance ÷ (Seepage velocity x retardation factor)
519 ft ÷ (221 ft/yr x 1.0) = 2.3 yrs

TRANSECT 4: Distance ÷ (Seepage velocity x retardation factor)
729 ft ÷ (221 ft/yr x 1.0) = 3.3 yrs

The travel time is an approximation for how long downgradient compartments receive the benefits of naturally-occurring upgradient source decay.

SUMMARY - EXAMPLE 1: BASELINE MTBE REMEDIATION TIMEFRAME

The approximation for flushing time indicates that each transect zone will take between 40 and 43 years to remediate based on natural attenuation alone.

EXAMPLE 2: REMEDIATION WITH SOIL VAPOR EXTRACTION

Problem:

Determine the control point concentration for remediation with soil vapor extraction (SVE) for the vadose zone. For simplicity, assume that SVE at this site does not affect the smear zone MTBE mass.

Solution:

Step MFAR-1. Calculate the After-Remediation Vadose Zone to Groundwater Mass Flux

The baseline vadose zone to groundwater mass flux (determined in the baseline Example 1) is:
w_b_{vd} = 3.0 g/day

Based on engineering judgement and the references in Section 5, assume that SVE reduces the MTBE flux from the vadose zone by 90%. Therefore, the flux reduction factor for this technology is:
rw_{vd} = 0.1

Hence, the vadose zone mass flux after remediation is
w_ar_{vd} = (3.0)(0.1) = 0.3 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

Step MFAR-2 Calculate the After-Remediation Smear Zone-to-Groundwater Mass Flux

The baseline smear zone-to-groundwater mass flux (determined in the baseline Example 1) is:
w_b_{sm} = 165 g/day

For this example, SVE is assumed to have no effect on the smear zone, and therefore the flux reduction factor for the smear zone is:
rw_{sm} = 1.0

Therefore, the smear zone mass flux after remediation is
w_ar_{sm} = (165)(1.0) = 165 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

Step MFAR-3. Calculate the After-Remediation Total Source-to-GW Mass Flux

The total source-to-gw zone to groundwater mass flux after remediation is:
w_ar_{ts} = 0.3 + 165 = 165.3 g/day
The baseline total source-to-groundwater mass flux (determined in the baseline Example 1) is:
w_b_{ts} = 168 g/day

Dividing w_ar_{ts} by w_b_{ts} gives the total source-to-gw flux reduction factor rw_{ts} :
rw_{ts} = 165.3 / 168 = 0.98

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

Step MFAR-4. Calculate the After-Remediation Transect Zone Mass Fluxes

TRANSECT ZONE 1

The baseline Transect 1 zone mass flux (determined in the baseline example above) is:
w_b_{gw-1} = 112 g/day

SVE has no direct effect on dissolved phase concentrations. Therefore, the flux reduction factor for Transect Zone 1 is: rw_{gw-1} = 1.0

The cumulative flux reduction factor for Transect Zone 1 is: rw_ar_{gw-1} = (0.98)(1.0) = 0.98

Therefore, the total Transect 1 zone mass flux after remediation is:
w_ar_{gw-1} = (112)(0.98) = 110 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

TRANSECT ZONE 2

The baseline Transect 2 zone mass flux is:
w_b_{gw-2} = 52 g/day

For SVE, the flux reduction factor for Transect Zone 2 is:
rw_{gw-2} = 1.0

The cumulative flux reduction factor for Transect Zone 2 is:
rw_ar_{gw-2} = (0.98)(1.0)(1.0) = 0.98

Therefore, the total Transect 2 zone mass flux after remediation is:
w_ar_{gw-2} = (52)(0.98) = 51 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

TRANSECT ZONE 3

The baseline Transect 3 zone to groundwater mass flux is:
w_b_{gw-3} = 18 g/day.

For SVE, the flux reduction factor for Transect Zone 3 is:
rw_{gw-3} = 1.0

The cumulative flux reduction factor for Transect Zone 3 is:
rw_ar_{gw-3} = (0.98)(1.0)(1.0)(1.0) = 0.98

Therefore, the total Transect 3 zone mass flux after remediation is:
w_ar_{gw-3} = (18)(0.98) = 17.6 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

TRANSECT ZONE 4

The baseline Transect 4 zone to groundwater mass flux is:
w_b_{gw-4} = 5.1 g/day

For SVE the flux reduction factor for Transect Zone 4 is:
rw_{gw-4} = 1.0

The cumulative flux reduction factor for Transect Zone 4 is:
rw_ar_{gw-4} = (0.98)(1.0)(1.0)(1.0)(1.0) = 0.98

Therefore, the total Transect 4 zone mass flux after remediation is:
w_ar_{gw-4} = (5.0)(0.98) = 5.0 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

Step MFAR-5. Calculate the After-Remediation Control Point Concentration

From Step MFAR-4:
w_ar_{gw-4} = 5.0 g/day

There are no controls at the control point, so rw_{pou} = 1.0.

The control point mass flux after remediation is:
w_ar_{gw-4} = 5.0 g/day

Therefore, the control point concentration after remediation for a flowrate of 54,504 L/day is:
C_ar_{cp} = (5.0 g/day)(1000 mg/g)/(54,504 L/day) = 0.090 mg/L

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 2

SUMMARY - EXAMPLE 2: REMEDIATION WITH SOIL VAPOR EXTRACTION

In this example, SVE is estimated to reduce the mass flux from the vadose zone by 90%. However, because most of the mass flux at the control point originates from the smear zone, the control point concentration changes only slightly, from 0.094 mg/L to 0.090 mg/L.

After Remediation Timeframe Steps RTAR-1 through RTAR-4

Because the reduction in the control point concentration is small, these steps are not performed for this example. See Example 3 for a description of these steps.

EXAMPLE 3: REMEDIATION WITH MULTI-PHASE EXTRACTION

Problem:

Determine the control point concentration for remediation with multi-phase extraction for the smear zone. For simplicity, assume that multi-phase extraction at this site does not affect the vadose zone mass.

Solution:

Step MFAR-1. Calculate the After-Remediation Vadose Zone to Groundwater Mass Flux

The baseline vadose zone to groundwater mass flux (determined in the baseline Example 1) is:
w_b_{vd} = 3.0 g/day

Assume that multi-phase extraction is designed to address the smear zone only. Therefore, the flux reduction factor for this technology is:
rw_{vd} = 1.0

Hence, the vadose zone mass flux after remediation is:
w_ar_{vd} = (3.0)(1.0) = 3.0 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME - EXAMPLE 3

Step MFAR-2. Calculate the After-Remediation Smear Zone-to-Groundwater Mass Flux

The baseline smear zone-to-groundwater mass flux (determined in the baseline Example 1) is:
w_b_{sm} = 165 g/day

At this site, high permeability and numerous extraction wells indicates that multi-phase extraction can reduce the mass flux of MTBE from the smear zone by 90% (this will not be achievable at most sites), so the flux reduction factor for the smear zone is:
rw_{sm} = 0.1

Therefore, the smear zone mass flux after remediation is
w_ar_{sm} = (165)(0.1) = 16.5 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME- EXAMPLE 3

Step MFAR-3. Calculate the After-Remediation Total Source-To-GW Mass Flux

The total source-to-groundwater mass flux after remediation is:
w_ar_{ts} = 3.0 + 16.5 = 19.5 g/day
The baseline total source-to-groundwater mass flux (determined in the baseline Example 1) is:
w_b_{ts} = 168 g/day

Dividing w_ar_{ts} by w_b_{ts} gives the total source-to-gw flux reduction factor rw_{ts}:
rw_{ts} = 19.5 / 168 = 0.12

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 3

Step MFAR-4. Calculate the After-Remediation Transect Zone to Groundwater Mass Fluxes

<u>TRANSECT ZONE 1</u>

The baseline Transect 1 zone mass flux (determined in the baseline example above) is:
w_b_{gw-1} = 112 g/day

For multi-phase extraction, the flux reduction factor for Transect Zone 1 is:
rw_{gw-1} = 1.0

The cumulative flux reduction factor for Transect Zone 1 is:
rw_ar_{gw-1} = (0.12)(1.0) = 0.12

Therefore, the total Transect 1 zone mass flux after remediation is
w_ar_{gw-1} = (112)(0.12) = 13.4 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 3

<u>TRANSECT ZONE 2</u>

The baseline Transect 2 zone mass flux is:
w_b_{gw-2} = 52 g/day

For multi-phase extraction, the flux reduction factor for Transect Zone 2 is:
rw_{gw-2} = 1.0

The cumulative flux reduction factor for Transect Zone 2 is:
rw_ar_{gw-2} = (0.12)(1.0)(1.0) = 0.12

Therefore, the total Transect 2 zone mass flux after remediation is:
w_ar_{gw-2} = (52)(0.12) = 6.2 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 3

<u>TRANSECT ZONE 3</u>

The baseline Transect 3 zone to groundwater mass flux is:
w_b_{gw-3} = 18 g/day

For multi-phase extraction, the flux reduction factor for Transect Zone 3 is:
rw_{gw-3} = 1.0

The cumulative flux reduction factor for Transect Zone 3 is:
rw_ar_{gw-3} = (0.12)(1.0)(1.0)(1.0) = 0.12

Therefore, the total Transect 3 zone mass flux after remediation is:
w_ar_{gw-3} = (18)(0.12) = 2.2 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME – EXAMPLE 3

<u>TRANSECT ZONE 4</u>

The baseline Transect 4 zone to groundwater mass flux is:
w_b_{gw-4} = 5.0 g/day
For multi-phase extraction, the flux reduction factor for Transect Zone 4 is:
rw_{gw-4} = 1.0

The cumulative flux reduction factor for Transect Zone 4 is:
rw_ar_{gw-4} = (0.12)(1.0)(1.0)(1.0)(1.0) = 0.12

Therefore, the total Transect 4 zone mass flux after remediation is:
w_ar_{gw-4} = (5.0)(0.12) = 0.6 g/day

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME- EXAMPLE 3

Step MFAR-5. **Calculate the After-Remediation Control Point Concentration**

From Step MFAR-4,
w_ar_{gw-4} = 0.6 g/day

There are no controls at the control point so:
rw_{pou} = 1.0.

The control point mass flux after remediation is:
w_ar_{gw-4} = 0.6 g/day

Therefore, the control point concentration after remediation for a flowrate of 54,504 L/day is:
C_ar_{cp} = (0.6 g/day)(1000 mg/g)/(54,504 L/day) = 0.011 mg/L

Enter this value on Worksheet 2, REMEDIATION EVALUATION TOOL USING MASS FLUX AND REMEDIATION TIMEFRAME- EXAMPLE 3

SUMMARY - EXAMPLE 3: REMEDIATION WITH MULTI-PHASE EXTRACTION

In this example, multi-phase extraction is estimated to reduce the mass flux from the smear zone by 90% (this may not be achievable at most sites). This will translate to a reduction in the mass flux at the control point of 88% (flux reduction factor equal to 0.12), and reduces the control point concentration from 0.094 mg/L to 0.011 mg/L. This is considered to be acceptable in this example.

Step RTAR-1. **Calculate the After-Remediation Vadose Zone Remediation Timeframe (t_ar_{vd}) (Optional)**

Based on the assumption that multi-phase extraction has little benefit on the vadose zone, the remediation timeframe is estimated to remain unchanged from the baseline value (t_b_{vd} = 20 years) so that t_ar_{vd} = 20 years. Enter this value on Worksheet 2.

Step RTAR-2. **Calculate the After-Remediation Smear Zone Mass (M_ar_{sm}) and Remediation Timeframe (t_ar_{sm}) (Optional)**

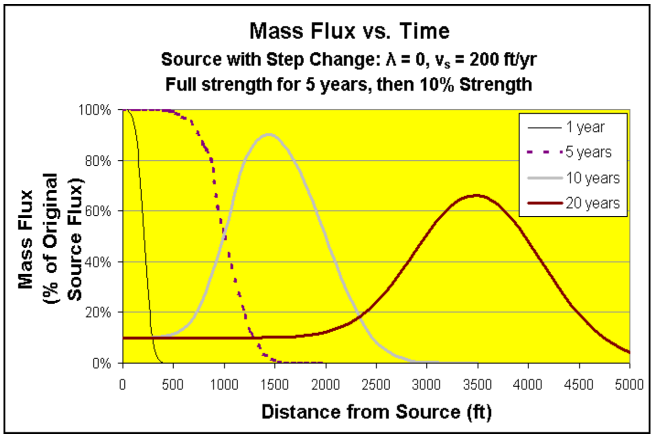
Based on techniques described in section 4, the 90% reduction in mass of the smear zone due to multi-phase extraction is expected to reduce the remediation timeframe by 90%, from 40 years to 4 years. Enter this value on Worksheet 2.

Step RTAR-3. **Select Mass Flux Curve in Appendix A That Best Represents Source**

The smear zone mass flux, which contributes the largest flux to groundwater, will be reduced by 90%. A residual source, consisting of the vadose zone and the 10% of the smear zone MTBE that is not removed, will persist for a longer time period. The closest match for this source configuration is a Step-Function source, with a 90% reduction in the mass flux after remediation. Because the seepage velocity at the site is best represented by the 200 ft/yr panel, select the bottom right hand graph on page A-14 of Appendix A .

Step RTAR-4. **Estimate the Transect Zone Remediation Timeframe (t_ar_{gw-1} to t_ar_{gw-4})**

Evaluate the bottom right hand graph on page A-14 of Appendix A (reproduced below) to see how quickly a change in mass flux is reflected in the downgradient mass flux. This graph is for a source that has been in place for 5 years at full strength, followed by a 90% reduction in source strength. The site has a seepage velocity of 200 ft/yr, and no MTBE biodegradation in the plume is assumed.



At this site, the control point is approximately 830 ft downgradient of the source. Based on the mass flux vs. time graph, the reduction in flux at the control point will follow this pattern:

At 1 year after the release, the flux at 830 ft will be near zero, as the plume has not approached the control point yet.

At 5 years after the release (and at the time remediation is performed), the flux at 830 ft will be at 90% of the maximum pre-remediation steady-state flux at the source, as dispersion has some effect on reducing the concentration at the control point.

At 10 years after the release (equal to 5 years after remediation as this graph assumes the source is at full strength for 5 years, then remediation occurs), the flux at 830 ft will be at about 30% of the maximum steady-state flux at the source due to the remediation effort. A larger slug of MTBE has passed the control point (a peak flux of 90% of the original pre-remediation flux is present at 1600 ft from the source), but the beneficial effects of remediation are being felt at the control point located 830 ft downgradient of the source.

At 20 years after the release (equal to 15 years after remediation as this graph assumes the source is at full strength for 5 years, then remediation occurs), the flux at 830 ft will be at about 10% of the maximum steady-state flux at the source because the plume is now at a new steady-state condition with the new post-remediation source term.

Therefore enter 15 years for Step RTAR-4 on Worksheet 2.

(Note that the use of the graphs is designed to give an approximate picture of the response of the mass flux in the plume due to changes in upstream flux. For a more accurate representation, a solute transport model could be used that would reflect actual site conditions and changes in the source.)

<u>IMPORTANT POINT:</u> If natural flushing and source remediation of downgradient transects take too long, then active remediation of a transect zone may be required. In this case, use the methods described in Section 5 to select technologies that address the groundwater compartment, and use the methods in Section 4 to estimate how long remediation may take.

SUMMARY - EXAMPLE 3: REMEDIATION TIMEFRAME WITH MULTI-PHASE EXTRACTION

These results indicate that it will take approximately 15 years for the benefits of source remediation to impact the control point. If this is too long to meet site remediation objectives, then fill out another worksheet for an alternative that includes active remediation of the groundwater transect zones (such as pump-and-treat).

EXAMPLE 4: POINT-OF-USE CONTROL

For this example, fill out a new Worksheet 2 with the same mass fluxes everywhere as in Example 1 Baseline except for the fluxes in the control point calculation.

Assume that a Point-of-Use control such as activated carbon will be applied at the well with 99.9% reduction in MTBE concentration in the well. Therefore, the point-of-use reduction factor is:
rw_{pou} = 0.001

If the baseline flux at the control point is 5.0 g/day, and rw_{pou} = 0.001, then the control point mass flux after remediation is:
w_ar_{cp} = (5.0)(0.001) = 0.005 g/day.

To get the resulting control point concentration, divide by the control point flowrate (54,504 L/day) and multiply by 1000 mg/g:

C_ar_{cp} = (0.005)(1000) / 54,504 = 0.000092 mg/L. This is an acceptable concentration.

SUMMARY - EXAMPLE 4: POINT-OF-USE CONTROL

A point-of-use control, such as activated carbon located at the extraction well, will be effective at controlling MTBE in the produced water.

WORKSHEET 1: BASELINE MASS FLUX AND REMEDIATION TIMEFRAME

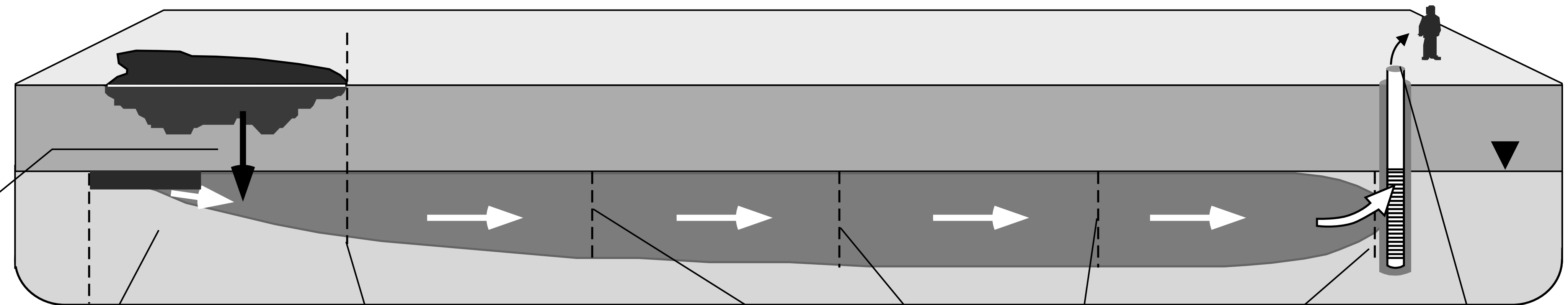
Site Name	*EXAMPLE 1 - BASELINE MTBE FLUXES*
Description	*UST - Elbert, Texas*
Date	*8/23/02*
Constituent	*MTBE*

WORKSHEET 1
BASELINE MASS FLUX and REMEDIATION TIMEFRAME TOOL
Groundwater Remediation Strategies Tool, American Petroleum Institute

Version 2.0
Issued: 8/18/03

OBJECTIVE
Determine best way to control impacts to groundwater.

APPROACH
A. Using RBCA or other decision-making methodology, determine if there is an unacceptable impact to groundwater. If yes:
B. Calculate up to seven mass flux terms:
vadose zone-to-groundwater;
smear zone-to-groundwater;
total source-to-groundwater;
up to four "transect zone."
C. Calculate control point concentration.
D. Estimate baseline remediation timeframes for compartments that are shown.
E. Go to Worksheet 2.



Step MFB-1
VADOSE ZONE-TO-GW FLUX
w_b_{vd} ***(Optional)***

w_b_{vd} VADOSE ZONE MASS FLUX (g/day): *3.0*

use methods in Section 3.5

Key Points:
w_b_{vd} is the Baseline Mass Flux prior to remediation. Compare this value to the After-Remediation Mass Flux on Worksheet 2 (**w_ar_{vd}**) to see how much the flux here and downgradient of this point is reduced.

The vadose zone flux calculation is *optional* , as in some cases an accurate estimation of the vadose zone flux is not possible.

Step MFB-3
SMEAR ZONE-TO-GW FLUX
w_b_{sm} ***(Optional)***

168 - *3.0* = *165*

w_b_{ts} (g/day) — w_b_{vd} (g/day) — **w_b_{sm} SMEAR ZONE MASS FLUX (g/day)**

Key Points:
w_b_{sm} is the Baseline Mass Flux prior to remediation. Compare this value to the After-Remediation Mass Flux on Worksheet 2 (**w_ar_{sm}**) to see how much the flux here and downgradient of this point is reduced. The smear zone flux (**w_b_{sm}**) is calculated indirectly by subtracting the vadose zone flux (**w_b_{vd}**) from the total flux from the source (**w_b_{ts}**). The smear zone flux calculation is *optional* .

Step MFB-2
TOTAL SOURCE-TO-GW$_{source}$ FLUX w_b_{ts}

w_b_{ts} GROUNDWATER TOTAL SOURCE MASS FLUX (g/day): *168*

use methods in Section 3.1, 3.2, or 3.3

Key Points:
w_b_{ts} is the Baseline Mass Flux prior to remediation. Compare this value to the After-Remediation Mass Flux (**w_ar_{ts}**) on Worksheet 2 to see how much the flux here and downgradient of this point is reduced.

w_b_{ts} is the total flux in groundwater leaving the source zone. If the vadose zone and smear zone mass fluxes are not calculated, this should be the starting point of the analysis.

Step MFB-4

GROUNDWATER TRANSECT AREA FLUXES	Transect Zone 1 Mass Flux	Transect Zone 2 Mass Flux	Transect Zone 3 Mass Flux	Transect Zone 4 Mass Flux
GROUNDWATER TRANSECT ZONE MASS FLUXES (g/day)	*112*	*52*	*18*	*5.1*
	w_b_{gw-1}	**w_b_{gw-2}**	**w_b_{gw-3}**	**w_b_{gw-4}**

use methods in Section 3.1, 3.2, or 3.3

Key Point:
w_b_{gw-1} through **w_b_{gw-4}** are the Baseline Mass Fluxes prior to remediation. Compare these values to the After-Remediation Mass Fluxes on Worksheet 2 to see how much the fluxes here and downgradient of these transects are reduced.

The intermediate transects allow you to evaluate a remedial action at a given point in the plume.

Step MFB-5
CONTROL POINT CONCENTRATION
(shown as well in this worksheet, but can also be surface water)

w_{gw-4} (g/day): *5.1*
÷
Control Point Flowrate (L/day): *54,504*
X 1000
=
C_b_{cp} CONTROL POINT CONCENTRATION (mg/L): *0.094*

see Section 3.4

Key Point:
C_b_{cp} is the Baseline Control Point concentration. Compare this value to the After-Remediation control point concentration (**C_ar_{cp}**) on Worksheet 2 to see how much the concentration has been reduced by remediation.

Step RTB-1
VADOSE ZONE MASS AND NATURAL ATTENUATION TIMEFRAME ***(Optional)***

t_b_{vd} VADOSE ZONE N.A. TIMEFRAME (yr): *20*

use methods in Section 4

Key Point:
t_b_{vd} is the Baseline Natural Attenuation Timeframe prior to remediation. Compare this value to the After-Remediation Vadose Zone Remediation Timeframe (**t_ar_{vd}**) on Worksheet 2 to see how much the timeframe is reduced by remediation.

Step RTB-2
SMEAR ZONE MASS AND NATURAL ATTENUATION TIMEFRAME ***(Optional)***

t_b_{sm} SMEAR ZONE N.A. TIMEFRAME (yr): *40*

use methods in Section 4

Key Point:
t_b_{sm} is the Baseline Natural Attenuation Timeframe prior to remediation. Compare this value to the After-Remediation Smear Zone Remediation Timeframe (**t_ar_{sm}**) on Worksheet 2 to see how much the timeframe is reduced by remediation.

Step RTB-3
TOTAL SOURCE ZONE NATURAL ATTENUATION TIMEFRAME ***(Optional)***

t_b_{ts} TOTAL SOURCE N.A. TIMEFRAME (yr): *40*

use maximum of ***t_b_{vd} and t_b_{sm}***

Key Point:
Use the maximum of either the baseline vadose zone natural attenuation timeframe (**t_b_{vd}**) and the baseline smear zone natural attenuation timeframe (**t_b_{sm}**).

t_b_{ts} is the Baseline natural attenuation timeframe prior to remediation. Compare this value to the After-Remediation Total Source Remediation Timeframe (**t_ar_{ts}**) on Worksheet 2 to see how much the timeframe is reduced by remediation.

Step RTB-4

GROUNDWATER TRANSECT ZONE MASS AND NATURAL ATTEN. TIMEFRAME	Transect Zone 1	Transect Zone 2	Transect Zone 3	Transect Zone 4
Travel Time To Transect (distance from source ÷ seepage velocity) (yr)	*0.6*	*1.5*	*2.3*	*3.3*
	+	+	+	+
t_b_{ts} Total Source Natural Attenuation Timeframe (yr)	*40*	*40*	*40*	*40*
	=	=	=	=
t_b_{gw} GROUNDWATER TRANSECT ZONE NATURAL ATTENUATION TIMEFRAMES (yr)	*~ 41*	*~ 42*	*~ 42*	*~ 43*
use methods in Section 4	**t_b_{gw-1}**	**t_b_{gw-2}**	**t_b_{gw-3}**	**t_b_{gw-4}**

Key Point:
t_b_{gw-1} through **t_b_{gw-4}** are the Baseline Natural Attenuation Timeframes prior to remediation. Compare these values to the After-Remediation Transect Zone Remediation Timeframes on Worksheet 2 to see how much the timeframes are reduced by remediation.

WORKSHEET 2: REMEDY EVALUATION

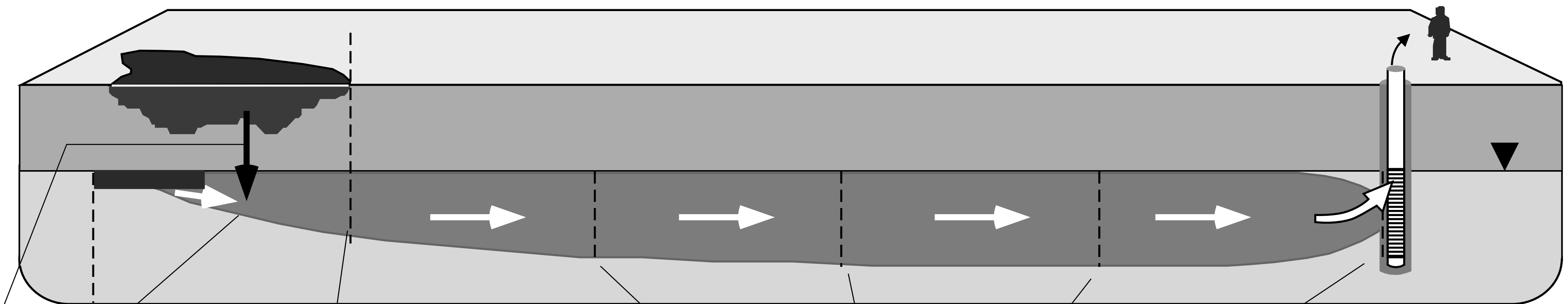
Site Name _EXAMPLE 2 - SVE_
Description _UST - Elbert, Texas_
Date _8/23/02_ Constituent _MTBE_

WORKSHEET 2
REMEDIATION EVALUATION TOOL USING MASS FLUX and REMEDIATION TIMEFRAME
Groundwater Remediation Strategies Tool, American Petroleum Institute

Version 2.0
Issued: 8/18/03

OBJECTIVE
Develop / document change of mass flux and remediation timeframe.

APPROACH
A. Calculate Baseline Mass Fluxes and Baseline Remediation Timeframes using Worksheet 1.
B. Select a candidate remedial technology or combination of technologies and:
   1. Estimate and enter the Flux Reduction Factor and Mass Reduction Factor for that remedy (see Section 5);
   2. Estimate the Mass Flux After Remediation (**ar**) (see Section 3);
   3. Estimate the After-Remediation and Remediation Timeframes (see Section 4);
   4. Evaluate how long it will take upgradient remediation activities to affect downgradient transport compartments (see Section 6).
C. Repeat this process for several remedial alternatives, and comparebased on reduction in mass flux, reduction in remediation, reliability, cost, and other factors.



Step MFAR-1
VADOSE ZONE-TO-GW FLUX w_ar_{vd} *(Optional)*

- w_b_{vd} (g/day): 3.0 *(from WrkSht1)*
- Technology: SVE
- X
- Flux Reduction Factor (rw_{vd}): 0.1
- *use resources in Section 5*
- =
- w_ar_{vd} VAD. ZONE MASS FLUX AFTER REMEDIATION (g/day): 0.3

+

Key Point:
w_ar_{vd} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The vadose zone flux calculation is *optional.*

Step MFAR-2
SMEAR ZONE-TO-GW FLUX w_ar_{sm} *(Optional)*

- w_b_{sm} (g/day): 165 *(from WrkSht1)*
- Technology: none
- X
- Flux Reduction Factor (rw_{sm}): 1.0
- *use resources in Section 5*
- =
- w_ar_{sm} SMEAR Z. MASS FLUX AFTER REMEDIATION (g/day): 165

=

Key Point:
w_ar_{sm} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The smear zone flux calculation is *optional.*

Step MFAR-3
TOTAL SOURCE-TO-GW$_{source}$ FLUX w_ar_{ts}

- w_ar_{ts} Total Source Flux After Remediation (g/day): 165.3
- ÷
- w_b_{ts} (g/day): 168 *(from WrkSht1)*
- =
- FLUX REDUCTION FACTOR (rw_{ts}): 0.98

Key Point:
w_ar_{ts} is the total mass flux to groundwater from the source zone after remediation. w_ar_{ts} can also be calculated by adding $w\_ar_{vd} + w\_ar_{sm}$. Continue the calculations to the right to determine the downgradient impact of this remedial alternative.

Step MFAR-4

GROUNDWATER TRANSECT ZONE FLUXES $w\_ar_{gw\text{-}x}$	TRANSECT ZONE 1 FLUX	TRANSECT ZONE 2 FLUX	TRANSECT ZONE 3 FLUX	TRANSECT ZONE 4 FLUX
Transect Zone Flux (g/day)	112 *(from WrkSht1)* $w\_b_{gw\text{-}1}$	52 *(from WrkSht1)* $w\_b_{gw\text{-}2}$	18 *(from WrkSht1)* $w\_b_{gw\text{-}3}$	5.1 *(from WrkSht1)* $w\_b_{gw\text{-}4}$
Technology: none	X	X	X	X
Flux Reduction Factor (rw_{gw}) *use resources in Section 5*	1.0 $rw_{gw\text{-}1}$	1.0 $rw_{gw\text{-}2}$	1.0 $rw_{gw\text{-}3}$	1.0 $rw_{gw\text{-}4}$
	X	X	X	X
	0.98 rw_{ts}	0.98 rw_{ts} x $rw_{gw\text{-}1}$ =	0.98 rw_{ts} x $rw_{gw\text{-}1}$ x $rw_{gw\text{-}2}$ =	0.98 rw_{ts} x $rw_{gw\text{-}1}$ x $rw_{gw\text{-}2}$ x $rw_{gw\text{-}3}$ =
TRANSECT ZONE MASS FLUX AFTER REMEDIATION (g/day)	110 $w\_ar_{gw\text{-}1}$	51 $w\_ar_{gw\text{-}2}$	17.6 $w\_ar_{gw\text{-}3}$	5.0 $w\_ar_{gw\text{-}4}$

Key Point:
Calculate the flux reduction factor for each transect zone being used. Add any flux reduction factors that have occurred in the source zone to reflect upstream remediation efforts. Note that the final flux being reported is the long-term flux after the system has reached equilibrium with the new, remediated transport compartments located upstream. To determine how long it might take to reach the after-remediation fluxes, use the charts in Section 6.

Step MFAR-5
CONTROL POINT CONCENTRATION (shown as well in this worksheet, but can also be surface water)

- $w\_ar_{gw\text{-}4}$ (g/day): 5.0
- X
- Control Point-of-Use (POU) Flux Reduction Factor (rw_{pou}): 1.0
- =
- w_ar_{cp} Control Point Mass Flux After Remediation (g/day): 5.0
- ÷
- Control Point Flowrate (L/day): 54,504
- X 1000
- =
- C_ar_{cp} CONTROL POINT CONCENTRATION AFTER REMEDIATION (mg/L): 0.090

see Section 3.4

Key Point:
The control point flux reduction factor can be used if point-of-use treatment such as carbon adsorption or air stripping is being used as part of the remedy.

This calculation shows the estimated concentration at the control point after remediation.

How Long Does it Take?
Use the charts in **Section 6 and Appendix A** to estimate how long upstream changes in mass flux will take to affect the mass flux downgradient.

Step RTAR-1
VADOSE ZONE REMEDIATION TIMEFRAME t_ar_{vd} *(Optional)*

- VADOSE ZONE REMEDIATION TIMEFRAME AFTER REMEDIATION (yr): Not Calc.
- *use methods in Section 4*

Key Point:
t_ar_{vd} represents the after-remediation remediation timeframe for the vadose zone. This calculation is *optional* .

Step RTAR-2
SMEAR ZONE REMEDIATION TIMEFRAME t_ar_{sm} *(Optional)*

- SMEAR ZONE REM. TIMEFRAME AFTER REMEDIATION (yr): Not Calc.
- *use methods in Section 4*

Key Point:
t_ar_{sm} represents the after-remediation remediation timeframe for the smear zone. This calculation is *optional* .

Step RTAR-3
SELECT MASS FLUX CURVE FROM APPENDIX B *(Optional)*

Is source mass flux vs. time during and after remediation represented better by:
- ☐ Decaying Source?
- ☐ Step Function Source?

Which mass flux curve in Appendix A best represents source mass flux during and after remediation? Not Calc.

Key Point:
Use results from Step RTAR-1 and RTAR-2 and the methods shown in Section 6 and Appendix A to select a mass flux curve that best represents this source during and after remediation.

Step RTAR-4

GROUNDWATER TRANSECT ZONE REMEDIATION TIME-FRAMES	TRANSECT ZONE 1 Timeframe	TRANSECT ZONE 2 Timeframe	TRANSECT ZONE 3 Timeframe	TRANSECT ZONE 4 Timeframe
TRANSECT ZONE REMEDIATION TIMEFRAME (yr) *use methods in Section 6*	Not Calc. $t\_ar_{gw\text{-}1}$	Not Calc. $t\_ar_{gw\text{-}2}$	Not Calc. $t\_ar_{gw\text{-}3}$	Not Calc. $t\_ar_{gw\text{-}4}$

Key Point:
Method 1: If there is no active remediation in the Transect Zones, use the methods shown in Section 6 and Appendix A to evaluate the timing of upgradient remediation activities on the transect zones. This calculation is *optional* .
Method 2: If there is active remediation in the Transect Zones (such as pump-and-treat), use the methods shown in Section 4 and 6 to estimate the remediation timeframe. This calculation is *optional* .

WORKSHEET 2: REMEDY EVALUATION

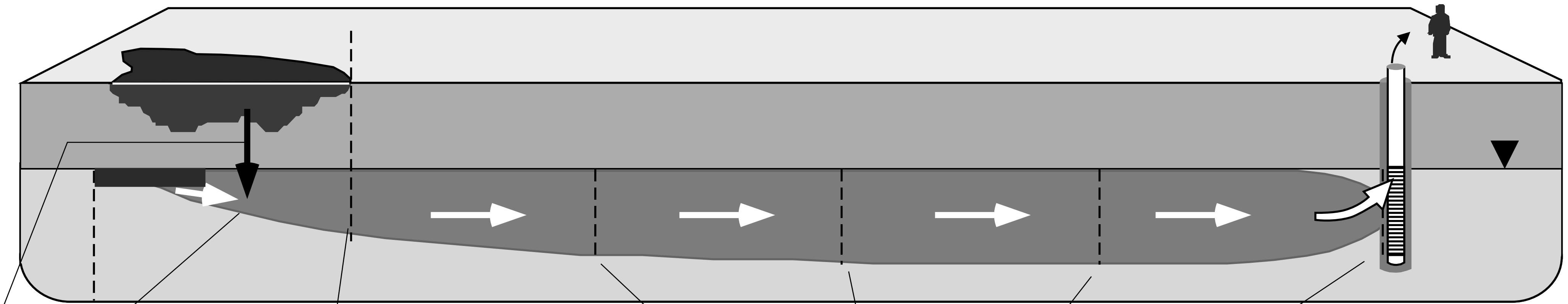
Site Name	*EXAMPLE 3 - Multi-Phase Extraction*
Description	*UST - Elbert, Texas*
Date	*8/23/02*
Constituent	*MTBE*

WORKSHEET 2
REMEDIATION EVALUATION TOOL USING MASS FLUX and REMEDIATION TIMEFRAME
Groundwater Remediation Strategies Tool, American Petroleum Institute

Version 2.0
Issued: 8/18/03

OBJECTIVE
Develop / document change of mass flux and remediation timeframe.

APPROACH
A. Calculate Baseline Mass Fluxes and Baseline Remediation Timeframes using Worksheet 1.
B. Select a candidate remedial technology or combination of technologies and:
  1. Estimate and enter the Flux Reduction Factor and Mass Reduction Factor for that remedy (see Section 5);
  2. Estimate the Mass Flux After Remediation (**ar**) (see Section 3);
  3. Estimate the After-Remediation and Remediation Timeframes (see Section 4);
  4. Evaluate how long it will take upgradient remediation activities to affect downgradient transport compartments (see Section 6).
C. Repeat this process for several remedial alternatives, and comparebased on reduction in mass flux, reduction in remediation, reliability, cost, and other factors.



Step MFAR-1
VADOSE ZONE-TO-GW FLUX w_ar_{vd} *(Optional)*

w_b_{vd} (g/day)	3.0 (from WrkSht1)
Technology: None	X
Flux Reduction Factor (rw_{vd})	1.0
use resources in Section 5	=
w_ar_{vd} VAD. ZONE MASS FLUX AFTER REMEDIATION (g/day)	3.0

+

Key Point:
w_ar_{vd} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The vadose zone flux calculation is *optional.*

Step MFAR-2
SMEAR ZONE-TO-GW FLUX w_ar_{sm} *(Optional)*

w_b_{sm} (g/day)	165 (from WrkSht1)
Technology: multi-phase	X
Flux Reduction Factor (rw_{sm})	0.1
use resources in Section 5	=
w_ar_{sm} SMEAR Z. MASS FLUX AFTER REMEDIATION (g/day)	16.5

=

Key Point:
w_ar_{sm} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The smear zone flux calcula-tion is *optional.*

Step MFAR-3
TOTAL SOURCE-TO-GW$_{source}$ FLUX w_ar_{ts}

w_ar_{ts} Total Source Flux After Remediation (g/day)	19.5
	÷
w_b_{ts} (g/day)	168 (from WrkSht1)
	=
FLUX REDUCTION FACTOR (rw_{ts})	0.12

Key Point:
w_ar_{ts} is the total mass flux to groundwater from the source zone after remediation. w_ar_{ts} can also be calculat-ed by adding w_ar_{vd} + w_ar_{sm}. Continue the calculations to the right to determine the downgradient impact of this remedial alternative.

Step MFAR-4

GROUNDWATER TRANSECT ZONE FLUXES w_ar_{gw-x}	TRANSECT ZONE 1 FLUX	TRANSECT ZONE 2 FLUX	TRANSECT ZONE 3 FLUX	TRANSECT ZONE 4 FLUX
Transect Zone Flux (g/day)	112 (from WrkSht1) w_b_{gw-1}	52 (from WrkSht1) w_b_{gw-2}	18 (from WrkSht1) w_b_{gw-3}	5.1 (from WrkSht1) w_b_{gw-4}
Technology: none	X	X	X	X
Flux Reduction Factor (rw_{gw}) *use resources in Section 5*	1.0 rw_{gw-1}	1.0 rw_{gw-2}	1.0 rw_{gw-3}	1.0 rw_{gw-4}
	X	X	X	X
	0.12 rw_{ts}	0.12 rw_{ts} x rw_{gw-1} =	0.12 rw_{ts} x rw_{gw-1} x rw_{gw-2} =	0.12 rw_{ts} x rw_{gw-1} x rw_{gw-2} x rw_{gw-3} =
TRANSECT ZONE MASS FLUX AFTER REMEDIATION (g/day)	13.4 w_ar_{gw-1}	6.2 w_ar_{gw-2}	2.2 w_ar_{gw-3}	0.6 w_ar_{gw-4}

Key Point:
Calculate the flux reduction factor for each transect zone being used. Add any flux reduction factors that have occurred in the source zone to reflect upstream remediation efforts. Note that the final flux being reported is the long-term flux after the system has reached equilibri-um with the new, remediated transport compartments located upstream. To determine how long it might take to reach the after-remediation fluxes, use the charts in Section 6.

Step MFAR-5
CONTROL POINT CONCENTRATION (shown as well in this worksheet, but can also be surface water)

w_ar_{gw-4} (g/day)	0.6
	X
Control Point-of-Use (POU) Flux Reduction Factor (rw_{pou})	1.0
	=
w_ar_{cp} Control Point Mass Flux After Remediation (g/day)	0.6
	÷
Control Point Flowrate (L/day)	54,504
	X 1000 =
C_ar_{cp} CONTROL POINT CONCENTRATION AFTER REMEDIATION (mg/L)	0.011

see Section 3.4

Key Point:
The control point flux reduction factor can be used if point-of-use treatment such as carbon adsorption or air stripping is being used as part of the remedy.

This calculation shows the estimated concentration at the control point after remediation.

How Long Does it Take?
Use the charts in **Section 6 and Appendix A** to estimate how long upstream changes in mass flux will take to affect the mass flux downgradient.

Step RTAR-1
VADOSE ZONE REMEDIATION TIMEFRAME t_ar_{vd} *(Optional)*

VADOSE ZONE REMEDIATION TIMEFRAME AFTER REMEDIATION (yr)	20

use methods in Section 4

Key Point:
t_ar_{vd} represents the after-remediation remediation timeframe for the vadose zone. This calculation is *optional* .

Step RTAR-2
SMEAR ZONE REMEDIATION TIMEFRAME t_ar_{sm} *(Optional)*

SMEAR ZONE REM. TIMEFRAME AFTER REMEDIATION (yr)	4

use methods in Section 4

Key Point:
t_ar_{sm} represents the after-remediation remediation timeframe for the smear zone. This calculation is *optional* .

Step RTAR-3
SELECT MASS FLUX CURVE FROM APPENDIX B *(Optional)*

Is source mass flux vs. time during adn after remediation rep-resented better by:
- [ ] Decaying Source?
- [x] Step Function Source?

Which mass flux curve in Appendix A best represents source mass flux during and after remediation? *see pg. A-14 bottom right panel*

Key Point:
Use results from Step RTAR-1 and RTAR-2 and the methods shown in Section 6 and Appendix A to select a mass flux curve that best represents this source during and after remediation.

Step RTAR-4

GROUNDWATER TRANSECT ZONE REMEDIATION TIME-FRAMES	TRANSECT ZONE 1 Timeframe	TRANSECT ZONE 2 Timeframe	TRANSECT ZONE 3 Timeframe	TRANSECT ZONE 4 Timeframe
TRANSECT ZONE REMEDIATION TIMEFRAME (yr) *use methods in Section 6*	10 t_ar_{gw-1}	10 t_ar_{gw-2}	10 t_ar_{gw-3}	10 t_ar_{gw-4}

Key Point:
Method 1: If there is no active remediation in the Transect Zones, use the meth-ods shown in Section 6 and Appendix A to evaluate the timing of upgradient remediation activities on the transect zones. This calculation is *optional* .
Method 2: If there is active remediation in the Transect Zones (such as pump-and-treat), use the methods shown in Section 4 and 6 to estimate the remediation timeframe. This calculation is *optional* .

WORKSHEET 2: REMEDY EVALUATION

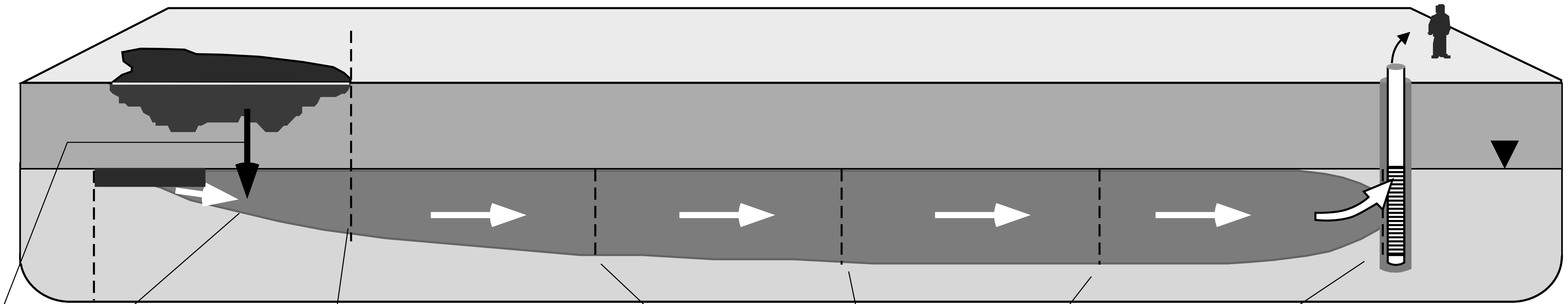
Site Name *EXAMPLE 4 - Point-of-Use Treatment*
Description *UST - Elbert, Texas*
Date *8/23/02* Constituent *MTBE*

WORKSHEET 2
REMEDIATION EVALUATION TOOL USING MASS FLUX and REMEDIATION TIMEFRAME
Groundwater Remediation Strategies Tool, American Petroleum Institute

Version 2.0
Issued: 8/18/03

OBJECTIVE
Develop / document change of mass flux and remediation timeframe.

APPROACH
A. Calculate Baseline Mass Fluxes and Baseline Remediation Timeframes using Worksheet 1.
B. Select a candidate remedial technology or combination of technologies and:
  1. Estimate and enter the Flux Reduction Factor and Mass Reduction Factor for that remedy (see Section 5);
  2. Estimate the Mass Flux After Remediation (**ar**) (see Section 3);
  3. Estimate the After-Remediation and Remediation Timeframes (see Section 4);
  4. Evaluate how long it will take upgradient remediation activities to affect downgradient transport compartments (see Section 6).
C. Repeat this process for several remedial alternatives, and comparebased on reduction in mass flux, reduction in remediation, reliability, cost, and other factors.



Step MFAR-1
VADOSE ZONE-TO-GW FLUX w_ar_{vd} *(Optional)*

w_b_{vd} (g/day)	*3.0* (from WrkSht1)
Technology: *None*	X
Flux Reduction Factor (rw_{vd})	*1.0*
use resources in Section 5	=
w_ar_{vd} VAD. ZONE MASS FLUX AFTER REMEDIATION (g/day)	*3.0*

+

Step MFAR-2
SMEAR ZONE-TO-GW FLUX w_ar_{sm} *(Optional)*

w_b_{sm} (g/day)	*165* (from WrkSht1)
Technology: *None*	X
Flux Reduction Factor (rw_{sm})	*1.0*
use resources in Section 5	=
w_ar_{sm} SMEAR Z. MASS FLUX AFTER REMEDIATION (g/day)	*165*

=

Step MFAR-3
TOTAL SOURCE-TO-GW$_{source}$ FLUX w_ar_{ts}

w_ar_{ts} Total Source Flux After Remediation (g/day)	*168*
	÷
w_b_{ts} (g/day)	*168* (from WrkSht1)
	=
FLUX REDUCTION FACTOR (rw_{ts})	*1.0*

Step MFAR-4

GROUNDWATER TRANSECT ZONE FLUXES w_ar_{gw-x}	TRANSECT ZONE 1 FLUX	TRANSECT ZONE 2 FLUX	TRANSECT ZONE 3 FLUX	TRANSECT ZONE 4 FLUX
Transect Zone Flux (g/day)	*112* (from WrkSht1) w_b_{gw-1}	*52* (from WrkSht1) w_b_{gw-2}	*18* (from WrkSht1) w_b_{gw-3}	*5.1* (from WrkSht1) w_b_{gw-4}
Technology: *none*	X	X	X	X
Flux Reduction Factor (rw_{gw}) *use resources in Section 5*	*1.0* rw_{gw-1}	*1.0* rw_{gw-2}	*1.0* rw_{gw-3}	*1.0* rw_{gw-4}
	X	X	X	X
	1.0 rw_{ts}	*1.0* rw_{ts} x rw_{gw-1} =	*1.0* rw_{ts} x rw_{gw-1} x rw_{gw-2} =	*1.0* rw_{ts} x rw_{gw-1} x rw_{gw-2} x rw_{gw-3} =
TRANSECT ZONE MASS FLUX AFTER REMEDIATION (g/day)	*112* w_ar_{gw-1}	*52* w_ar_{gw-2}	*18* w_ar_{gw-3}	*5.1* w_ar_{gw-4}

Step MFAR-5
CONTROL POINT CONCENTRATION (shown as well in this worksheet, but can also be surface water)

w_ar_{gw-4} (g/day)	*5.1*
	X
Control Point-of-Use (POU) Flux Reduction Factor (rw_{pou})	*0.001*
	=
w_ar_{cp} Control Point Mass Flux After Remediation (g/day)	*0.005*
	÷
Control Point Flowrate (L/day)	*54,504*
	X 1000 =
C_ar_{cp} CONTROL POINT CONCENTRATION AFTER REMEDIATION (mg/L)	*0.00009*

see Section 3.4

Key Point:
w_ar_{vd} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The vadose zone flux calculation is *optional.*

Key Point:
w_ar_{sm} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The smear zone flux calculation is *optional.*

Key Point:
w_ar_{ts} is the total mass flux to groundwater from the source zone after remediation. w_ar_{ts} can also be calculated by adding $w\_ar_{vd} + w\_ar_{sm}$. Continue the calculations to the right to determine the downgradient impact of this remedial alternative.

Key Point:
Calculate the flux reduction factor for each transect zone being used. Add any flux reduction factors that have occurred in the source zone to reflect upstream remediation efforts. Note that the final flux being reported is the long-term flux after the system has reached equilibrium with the new, remediated transport compartments located upstream. To determine how long it might take to reach the after-remediation fluxes, use the charts in Section 6.

Key Point:
The control point flux reduction factor can be used if point-of-use treatment such as carbon adsorption or air stripping is being used as part of the remedy.

This calculation shows the estimated concentration at the control point after remediation.

How Long Does it Take?
Use the charts in **Section 6 and Appendix A** to estimate how long upstream changes in mass flux will take to affect the mass flux downgradient.

Step RTAR-1
VADOSE ZONE REMEDIATION TIMEFRAME t_ar_{vd} *(Optional)*

VADOSE ZONE REMEDIATION TIMEFRAME AFTER REMEDIATION (yr)	*Not Calc.*

use methods in Section 4

Step RTAR-2
SMEAR ZONE REMEDIATION TIMEFRAME t_ar_{sm} *(Optional)*

SMEAR ZONE REM. TIMEFRAME AFTER REMEDIATION (yr)	*Not Calc.*

use methods in Section 4

Step RTAR-3
SELECT MASS FLUX CURVE FROM APPENDIX B *(Optional)*

Is source mass flux vs. time during adn after remediation represented better by:
☐ Decaying Source?
☐ Step Function Source?

Which mass flux curve in Appendix A best represents source mass flux during and after remediation?	*Not Calc.*

Step RTAR-4

GROUNDWATER TRANSECT ZONE REMEDIATION TIME-FRAMES	TRANSECT ZONE 1 Timeframe	TRANSECT ZONE 2 Timeframe	TRANSECT ZONE 3 Timeframe	TRANSECT ZONE 4 Timeframe
TRANSECT ZONE REMEDIATION TIMEFRAME (yr) *use methods in Section 6*	*Not Calc.* t_ar_{gw-1}	*Not Calc.* t_ar_{gw-2}	*Not Calc.* t_ar_{gw-3}	*Not Calc.* t_ar_{gw-4}

Key Point:
t_ar_{vd} represents the after-remediation remediation timeframe for the vadose zone. This calculation is *optional* .

Key Point:
t_ar_{sm} represents the after-remediation remediation timeframe for the smear zone. This calculation is *optional* .

Key Point:
Use results from Step RTAR-1 and RTAR-2 and the methods shown in Section 6 and Appendix A to select a mass flux curve that best represents this source during and after remediation.

Key Point:
Method 1: If there is no active remediation in the Transect Zones, use the methods shown in Section 6 and Appendix A to evaluate the timing of upgradient remediation activities on the transect zones. This calculation is *optional* .
Method 2: If there is active remediation in the Transect Zones (such as pump-and-treat), use the methods shown in Section 4 and 6 to estimate the remediation timeframe. This calculation is *optional* .

WORKSHEET 1: BASELINE MASS FLUX AND REMEDIATION TIMEFRAME

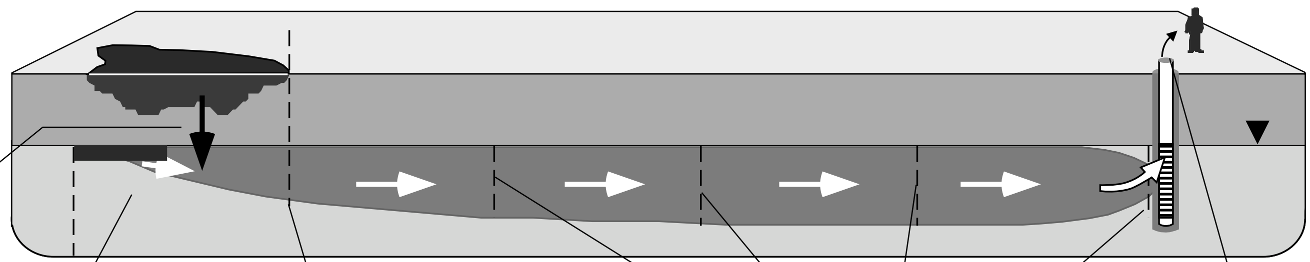
Site Name ______________________
Description ______________________
Date __________ Constituent __________

WORKSHEET 1
BASELINE MASS FLUX and REMEDIATION TIMEFRAME TOOL
Groundwater Remediation Strategies Tool, American Petroleum Institute

Version 2.0
Issued: 8/18/03

OBJECTIVE
Determine best way to control impacts to groundwater.

APPROACH
A. Using RBCA or other decision-making methodology, determine if there is an unacceptable impact to groundwater. If yes:
B. Calculate up to seven mass flux terms:
vadose zone-to-groundwater;
smear zone-to-groundwater;
total source-to-groundwater;
up to four "transect zone."
C. Calculate control point concentration.
D. Estimate baseline remediation timeframes for compartments that are shown.
E. Go to Worksheet 2.



Step MFB-1

VADOSE ZONE-TO-GW FLUX
w_b$_{vd}$ *(Optional)*

w_b$_{vd}$
VADOSE ZONE MASS FLUX (g/day) [ ]

use methods in Section 3.5

Key Points:
w_b$_{vd}$ is the Baseline Mass Flux prior to remediation. Compare this value to the After-Remediation Mass Flux on Worksheet 2 (**w_ar$_{vd}$**) to see how much the flux here and downgradient of this point is reduced.

The vadose zone flux calculation is *optional*, as in some cases an accurate estimation of the vadose zone flux is not possible.

Step MFB-3

SMEAR ZONE-TO-GW FLUX
w_b$_{sm}$ *(Optional)*

[ ] - [ ] = [ ]
w_b$_{ts}$ (g/day) w_b$_{vd}$ (g/day) **w_b$_{sm}$ SMEAR ZONE MASS FLUX (g/day)**

Key Points:
w_b$_{sm}$ is the Baseline Mass Flux prior to remediation. Compare this value to the After-Remediation Mass Flux on Worksheet 2 (**w_ar$_{sm}$**) to see how much the flux here and downgradient of this point is reduced. The smear zone flux (**w_b$_{sm}$**) is calculated indirectly by subtracting the vadose zone flux (**w_b$_{vd}$**) from the total flux from the source (w_b$_{ts}$). The smear zone flux calculation is *optional.*

Step MFB-2

TOTAL SOURCE-TO-GW$_{source}$ FLUX w_b$_{ts}$

w_b$_{ts}$
GROUNDWATER TOTAL SOURCE MASS FLUX (g/day) [ ]

use methods in Section 3.1, 3.2, or 3.3

Key Points:
w_b$_{ts}$ is the Baseline Mass Flux prior to remediation. Compare this value to the After-Remediation Mass Flux (**w_ar$_{ts}$**) on Worksheet 2 to see how much the flux here and downgradient of this point is reduced.
w_b$_{ts}$ is the total flux in groundwater leaving the source zone. If the vadose zone and smear zone mass fluxes are not calculated, this should be the starting point of the analysis.

Step MFB-4

GROUNDWATER TRANSECT AREA FLUXES	Transect Zone 1 Mass Flux	Transect Zone 2 Mass Flux	Transect Zone 3 Mass Flux	Transect Zone 4 Mass Flux
GROUNDWATER TRANSECT ZONE MASS FLUXES (g/day)	[ ] **w_b$_{gw-1}$**	[ ] **w_b$_{gw-2}$**	[ ] **w_b$_{gw-3}$**	[ ] **w_b$_{gw-4}$**

use methods in Section 3.1, 3.2, or 3.3

Key Point:
w_b$_{gw-1}$ through **w_b$_{gw-4}$** are the Baseline Mass Fluxes prior to remediation. Compare these values to the After-Remediation Mass Fluxes on Worksheet 2 to see how much the fluxes here and downgradient of these transects are reduced.

The intermediate transects allow you to evaluate a remedial action at a given point in the plume.

Step MFB-5

CONTROL POINT CONCENTRATION (shown as well in this worksheet, but can also be surface water)

w$_{gw-4}$ (g/day) [ ]
÷
Control Point Flowrate (L/day) [ ]
X 1000
=
C_b$_{cp}$
CONTROL POINT CONCENTRATION (mg/L) [ ]

see Section 3.4

Key Point:
C_b$_{cp}$ is the Baseline Control Point concentration. Compare this value to the After-Remediation control point concentration (**C_ar$_{cp}$**) on Worksheet 2 to see how much the concentration has been reduced by remediation.

Step RTB-1

VADOSE ZONE MASS AND NATURAL ATTENUATION TIMEFRAME *(Optional)*

t_b$_{vd}$
VADOSE ZONE N.A. TIMEFRAME (yr) [ ]

use methods in Section 4

Key Point:
t_b$_{vd}$ is the Baseline Natural Attenuation Timeframe prior to remediation. Compare this value to the After-Remediation Vadose Zone Remediation Timeframe (**t_ar$_{vd}$**) on Worksheet 2 to see how much the timeframe is reduced by remediation.

Step RTB-2

SMEAR ZONE MASS AND NATURAL ATTENUATION TIMEFRAME *(Optional)*

t_b$_{sm}$
SMEAR ZONE N.A. TIMEFRAME (yr) [ ]

use methods in Section 4

Key Point:
t_b$_{sm}$ is the Baseline Natural Attenuation Timeframe prior to remediation. Compare this value to the After-Remediation Smear Zone Remediation Timeframe (**t_ar$_{sm}$**) on Worksheet 2 to see how much the timeframe is reduced by remediation.

Step RTB-3

TOTAL SOURCE ZONE NATURAL ATTENUATION TIMEFRAME *(Optional)*

t_b$_{ts}$
TOTAL SOURCE N.A. TIMEFRAME (yr) [ ]

use maximum of t_b$_{vd}$ and t_b$_{sm}$

Key Point:
Use the maximum of either the baseline vadose zone natural attenuation timeframe (**t_b$_{vd}$**) and the baseline smear zone natural attenuation timeframe (**t_b$_{sm}$**).
t_b$_{ts}$ is the Baseline natural attenuation timeframe prior to remediation. Compare this value to the After-Remediation Total Source Remediation Timeframe (**t_ar$_{ts}$**) on Worksheet 2 to see how much the timeframe is reduced by remediation.

Step RTB-4

GROUNDWATER TRANSECT ZONE MASS AND NATURAL ATTEN. TIMEFRAME	Transect Zone 1	Transect Zone 2	Transect Zone 3	Transect Zone 4
Travel Time To Transect (distance from source ÷ seepage velocity) (yr)	[ ] +	[ ] +	[ ] +	[ ] +
t_b$_{ts}$ Total Source Natural Attenuation Timeframe (yr)	[ ] =	[ ] =	[ ] =	[ ] =
t_b$_{gw}$ GROUNDWATER TRANSECT ZONE NATURAL ATTENUATION TIMEFRAMES (yr) *use methods in Section 4*	[ ] **t_b$_{gw-1}$**	[ ] **t_b$_{gw-2}$**	[ ] **t_b$_{gw-3}$**	[ ] **t_b$_{gw-4}$**

Key Point:
t_b$_{gw-1}$ through **t_b$_{gw-4}$** are the Baseline Natural Attenuation Timeframes prior to remediation. Compare these values to the After-Remediation Transect Zone Remediation Timeframes on Worksheet 2 to see how much the timeframes are reduced by remediation.

WORKSHEET 2: REMEDY EVALUATION

Site Name ____________
Description ____________
Date ________ Constituent ________

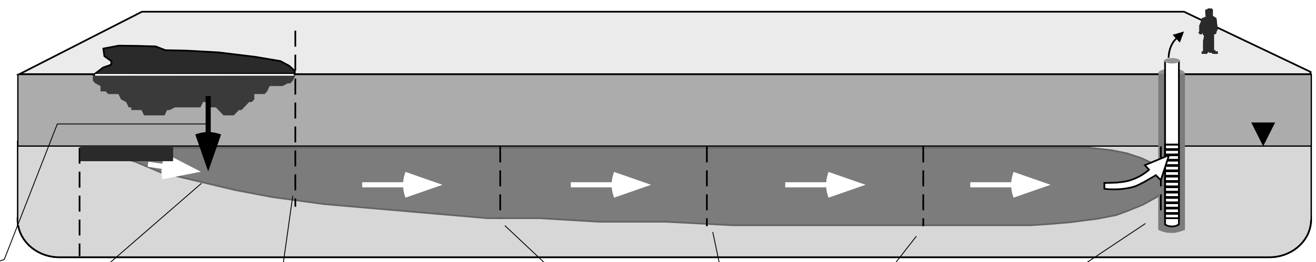
WORKSHEET 2
REMEDIATION EVALUATION TOOL USING MASS FLUX and REMEDIATION TIMEFRAME
Groundwater Remediation Strategies Tool, American Petroleum Institute

Version 2.0
Issued: 8/18/03

OBJECTIVE
Develop / document change of mass flux and remediation timeframe.

APPROACH
A. Calculate Baseline Mass Fluxes and Baseline Remediation Timeframes using Worksheet 1.
B. Select a candidate remedial technology or combination of technologies and:
1. Estimate and enter the Flux Reduction Factor and Mass Reduction Factor for that remedy (see Section 5);
2. Estimate the Mass Flux After Remediation (**ar**) (see Section 3);
3. Estimate the After-Remediation and Remediation Timeframes (see Section 4);
4. Evaluate how long it will take upgradient remediation activities to affect downgradient transport compartments (see Section 6).

C. Repeat this process for several remedial alternatives, and comparebased on reduction in mass flux, reduction in remediation, reliability, cost, and other factors.



Step MFAR-1
VADOSE ZONE-TO-GW FLUX w_ar_{vd} *(Optional)*

w_b_{vd} (g/day) [ ] *from WrkSht 1*
X
Technology: [ ]
Flux Reduction Factor (rw_{vd}) [ ]
use resources in Section 5
=
w_ar_{vd}
VAD. ZONE MASS FLUX AFTER REMEDIATION (g/day) [ ]

+

Key Point:
w_ar_{vd} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The vadose zone flux calculation is *optional.*

Step MFAR-2
SMEAR ZONE-TO-GW FLUX w_ar_{sm} *(Optional)*

w_b_{sm} (g/day) [ ] *from WrkSht 1*
X
Technology: [ ]
Flux Reduction Factor (rw_{sm}) [ ]
use resources in Section 5
=
w_ar_{sm}
SMEAR Z. MASS FLUX AFTER REMEDIATION (g/day) [ ]

=

Key Point:
w_ar_{sm} represents the after-remediation mass flux to groundwater. Continue the calculations to the right to determine the downgradient impact of this remedial alternative. The smear zone flux calculation is *optional.*

Step MFAR-3
TOTAL SOURCE-TO-GW$_{source}$ FLUX w_ar_{ts}

w_ar_{ts}
Total Source Flux After Remediation (g/day) [ ]
÷
w_b_{ts} (g/day) [ ] *from WrkSht 1*
=
FLUX REDUCTION FACTOR (rw_t) [ ]

Key Point:
w_ar_{ts} is the total mass flux to groundwater from the source zone after remediation. w_ar_{ts} can also be calculated by adding $w\_ar_{vd} + w\_ar_{sm}$.

Continue the calculations to the right to determine the downgradient impact of this remedial alternative.

Step MFAR-4

GROUNDWATER TRANSECT ZONE FLUXES $w\_ar_{gw\text{-}x}$	TRANSECT ZONE 1 FLUX	TRANSECT ZONE 2 FLUX	TRANSECT ZONE 3 FLUX	TRANSECT ZONE 4 FLUX
Transect Zone Flux (g/day)	*from WrkSht 1* $w\_b_{gw\text{-}1}$	*from WrkSht 1* $w\_b_{gw\text{-}2}$	*from WrkSht 1* $w\_b_{gw\text{-}3}$	*from WrkSht 1* $w\_b_{gw\text{-}4}$
	X	X	X	X
Technology: [ ] Flux Reduction Factor (rw_{gw}) *use resources in Section 5*	$rw_{gw\text{-}1}$	$rw_{gw\text{-}2}$	$rw_{gw\text{-}3}$	$rw_{gw\text{-}4}$
	X	X	X	X
	rw_{ts}	rw_{ts} x $rw_{gw\text{-}1}$ =	rw_{ts} x $rw_{gw\text{-}1}$ x $rw_{gw\text{-}2}$ =	rw_{ts} x $rw_{gw\text{-}1}$ x $rw_{gw\text{-}2}$ x $rw_{gw\text{-}3}$ =
TRANSECT ZONE MASS FLUX AFTER REMEDIATION (g/day)	$w\_ar_{gw\text{-}1}$	$w\_ar_{gw\text{-}2}$	$w\_ar_{gw\text{-}3}$	$w\_ar_{gw\text{-}4}$

Key Point:
Calculate the flux reduction factor for each transect zone being used. Add any flux reduction factors that have occurred in the source zone to reflect upstream remediation efforts. Note that the final al flux being reported is the long-term flux after the system has reached equilibrium wit the new, remediated transport compartments located upstream. To determine how long it might take to reach the after-remediation fluxes, use the charts in Section 6.

Step MFAR-5
CONTROL POINT CONCENTRATION (shown as well in this worksheet, but can also be surface water)

$w\_ar_{gw\text{-}4}$ (g/day) [ ]
X
Control Point-of-Use (POU) Flux Reduction Factor (rw_{pou}) [ ]
=
w_ar_{cp}
Control Point Mass Flux After Remediation (g/day) [ ]
÷
Control Point Flowrate (L/day) [ ]
X 1000
=
C_ar_{cp}
CONTROL POINT CONCENTRATION AFTER REMEDIATION (mg/L) [ ]
see Section 3.4

Key Point:
The control point flux reduction factor can be used if point-of-use treatment such as carbon adsorption or air stripping is being used as part of the remedy.

This calculation shows the estimated concentration at the control point after remediation.

How Long Does it Take?
Use the charts in **Section 6 and Appendix A** to estimate how long upstream changes in mass flux will take to affect the mass flux downgradient.

Step RTAR-1
VADOSE ZONE REMEDIATION TIMEFRAME t_ar_{vd} *(Optional)*

VADOSE ZONE REMEDIATION TIMEFRAME AFTER REMEDIATION (yr) [ ]
use methods in Section 4

Key Point:
t_ar_{vd} represents the after-remediation remediation timeframe for the vadose zone. This calculation is *optional* .

Step RTAR-2
SMEAR ZONE REMEDIATION TIMEFRAME t_ar_{sm} *(Optional)*

SMEAR ZONE REM. TIMEFRAME AFTER REMEDIATION (yr) [ ]
use methods in Section 4

Key Point:
t_ar_{sm} represents the after-remediation remediation timeframe for the smear zone. This calculation is *optional* .

Step RTAR-3
SELECT MASS FLUX CURVE FROM APPENDIX B *(Optional)*

Is source mass flux vs. time during adn after remediation represented better by:
[ ] Decaying Source?
[ ] Step Function Source?

Which mass flux curve in Appendix A best represents source mass flux during and after remediation? [ ]

Key Point:
Use results from Step RTAR-1 and RTAR-2 and the methods shown in Section 6 and Appendix A to select a mass flux curve that best represents this source during and after remediation.

Step RTAR-4

GROUNDWATER TRANSECT ZONE REMEDIATION TIME-FRAMES	TRANSECT ZONE 1 Time-frame	TRANSECT ZONE 2 Timeframe	TRANSECT ZONE 3 Timeframe	TRANSECT ZONE 4 Timeframe
TRANSECT ZONE REMEDIATION TIMEFRAME (yr) *use methods in Section 6*	$t\_ar_{gw\text{-}1}$	$t\_ar_{gw\text{-}2}$	$t\_ar_{gw\text{-}3}$	$t\_ar_{gw\text{-}4}$

Key Point:
Method 1: If there is no active remediation in the Transect Zones, use the methods shown in Section 6 and Appendix A to evaluate the timing of upgradient remediation activities on the transect zones. This calculation is *optional* .
Method 2: If there is active remediation in the Transect Zones (such as pump-and-treat), use the methods shown in Section 4 and 6 to estimate the remediation timeframe. This calculation is *optional* .

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