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ENVIRONMENTAL PROTECTION DIVISION

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Frequently Asked Questions for Evaluating the Soil-to-Groundwater Migration Pathway

October 18, 2019

Technical Guidance Document

Acknowledgement

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Additional EPD staff and management provided technical review of this document.

Guidelines for Applicability and Use of this Guidance Document

This document provides technical guidance for evaluating the soil-to-groundwater migration pathway when such an evaluation is required under the applicable Georgia statutes and regulations administered by the following programs of the Land Protection Branch:

- Hazardous Waste Corrective Action Program

- Hazardous Waste Management Program

- Response and Remediation Program

This guidance document is intended for use by environmental professionals who have experience in the investigation and remediation of subsurface contamination. The guidance provided within this document includes methods and recommendations that can be used to meet the pathway evaluation requirements of statutes and regulations; however, this document is not a statute or a regulation. This document may be revised in the future based on comments and/or new information. Using the methods and recommendations in this guidance document will provide for streamlined EPD review of soil-to-groundwater migration pathway evaluations. Other approaches can be accepted if they meet the requirements of applicable statutes and regulations. If another approach is being considered, EPD recommends discussing the approach with EPD staff involved with the project prior to implementation. The use of trade names does not constitute endorsement by EPD.

Contents

Acronyms

ASTM	American Society for Testing and Materials
CSM	Conceptual Site Model
DAF	Dilution Attenuation Factor
EPD	Georgia Environmental Protection Division
FAQs	Frequently Asked Questions
IDEM	Indiana Department of Environmental Management
MCL	Maximum Contaminant Level
NADP	National Atmospheric Deposition Program
NAPL	Non-Aqueous Phase Liquid
NJDEP	New Jersey Department of Environmental Protection
OCGA	Official Code of Georgia Annotated
RSL	Regional Screening Level
SESD	Science and Ecosystem Support Division
SESOIL	Seasonal Soil Model
SPLP	Synthetic Precipitation Leaching Procedure
SSL	Soil Screening Level
TCLP	Toxicity Characteristic Leaching Procedure
TNRCC	Texas Natural Resource Conservation Commission
TOC	Total Organic Carbon
UCL	Upper Confidence Limit
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VLEACH	Vadose Zone Leaching Model
WAC	Washington Administrative Code

Key Terms

C_f Acceptable Groundwater Concentration. The acceptable contaminant concentration in groundwater. Typically, the applicable groundwater cleanup standard.

C_L Field Leachate Concentration. The estimated leachate concentration under field conditions.

C_{sat} Soil Saturation Limit or Concentration. The contaminant concentration in soil at which the adsorptive limits of soil particles have been reached and pore air / pore water are saturated. Above this concentration, the contaminant may be present in free phase.

C_t Acceptable Soil Concentration. The contaminant concentration in soil that will not cause the contaminant concentration in groundwater to exceed the acceptable groundwater concentration.

C_T Total Contaminant Concentration in Soil. The contaminant concentration in soil, measured using a standard USEPA analytical method (e.g., SW-846 Method 8260) on a dry-weight basis.

C_w Target Soil Leachate Concentration. The maximum soil leachate concentration that, after dilution in groundwater, will not cause the groundwater concentration to exceed the acceptable level.

DAF   Dilution Attenuation Factor. The ratio of contaminant concentration in soil leachate to the concentration in groundwater at the receptor point.

Source Area For the purposes of this document, source area is defined as the extent of contamination, consistent with the definition in the USEPA *Soil Screening Guidance: User's Guide* (USEPA 1996a).

Purpose

The purpose of this document is to provide guidance for evaluating the soil-to-groundwater migration pathway at regulated sites in Georgia in a convenient question-and-answer format. This document is intended for use with sites that are subject to regulation by the Georgia Environmental Protection Division (EPD) under the following Georgia statutes and regulations:

Statutes:

- Hazardous Site Response Act (OCGA 12-8-90)

- Brownfield Act (OCGA 12-8-200)

- Hazardous Waste Management Act (OCGA 12-8-60)

- Voluntary Remediation Program Act (OCGA 12-8-100)

Regulations:

- Rules for Hazardous Site Response (Chapter 391-3-19)

- Rules for Hazardous Waste Management (Chapter 391-3-11)

Programs within the EPD Land Protection Branch administer regulatory oversight of these statutes and regulations. These programs and their contact information are shown in Table 1. For more information about Land Protection Branch programs, click here.

Table 1: Contact Information for Relevant EPD Regulatory Programs.

EPD Regulatory Program	Phone
Hazardous Waste Management Program	404.656.2833
Hazardous Waste Corrective Action Program	404.656.7802
Response and Remediation Program	404.657.8600

Frequently Asked Questions (FAQs)

1. What is the soil-to-groundwater migration pathway?

The soil-to-groundwater migration pathway is the pathway along which contaminants migrate from the vadose, or unsaturated, zone (soil) to the saturated zone (groundwater) by a process known as "leaching." During leaching, soil contaminants are released into the pore-waters of the soil, forming "leachate", which then percolates down into the underlying groundwater. If contaminants are present in free phase, they may migrate independently of pore water movement. The purpose of evaluating the soil-to-groundwater migration pathway is to determine acceptable contaminant concentrations in soil that will not cause contaminant concentrations in groundwater

to exceed acceptable levels at a regulatory point of compliance[1]. A conceptual model of the soil-to-groundwater migration pathway is shown in Figure 1. In this example, a receptor well is located a distance "x" downgradient from the source of contamination. Note that other receptors to contaminated groundwater could include surface water and building occupants via vapor intrusion.
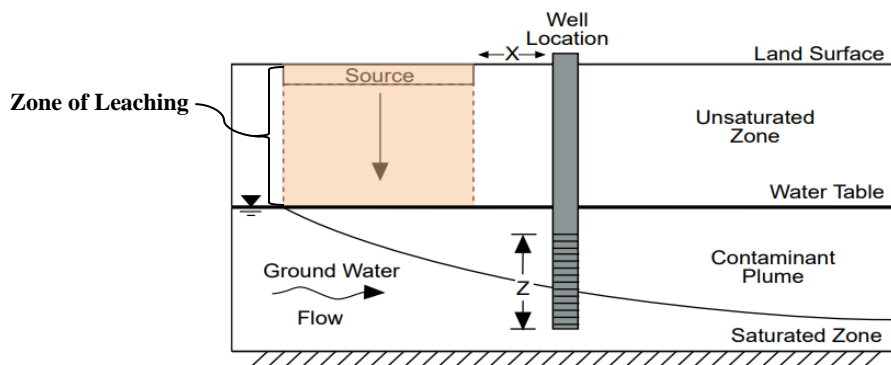

Figure 1: Conceptual model of the soil-to-groundwater migration pathway. Source: Adapted from USEPA 1996b.

2.   How do I evaluate the soil-to-groundwater migration pathway?

The soil-to-groundwater migration pathway may be evaluated using a laboratory leaching test and/or a fate and transport model approved by EPD. Laboratory tests may also be used to obtain site-specific parameters for input in fate and transport models. In cases where the soil release occurred many years ago and groundwater has not been impacted, a multiple lines of evidence approach can also be considered (see Question 9).

EPD recommends beginning the evaluation of the soil-to-groundwater migration pathway with Equation 10 of the United States Environmental Protection Agency (USEPA) *Soil Screening Guidance: User's Guide* (USEPA 1996a). In this document, the equation is referred to as the "Soil-Water Partition Equation" and it is presented as Equation 1. The Soil-Water Partition Equation is a conservative screening level model that can often be used with limited site-specific data. If desired, a more site-specific evaluation can then be performed by incorporating site-specific parameters in the Soil-Water Partition Equation, by using laboratory leaching tests, or by using a more advanced fate and transport model with site-specific input parameters.

Note: When using a model to develop acceptable soil concentrations, the assumptions of the model should be clearly stated, and the selection/determination of any input parameters should be justified and documented.

3.   How do I use the Soil-Water Partition Equation to evaluate the soil-to-groundwater migration pathway?

This section discusses the use of the Soil-Water Partition Equation to develop soil screening criteria for evaluating the soil-to-groundwater migration pathway. Note that the USEPA Regional

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[1] The determination of acceptable groundwater concentrations and the regulatory point of compliance are not addressed in this guidance document.

Screening Level (RSL) Calculator can be used to calculate results of the Soil-Water Partition Equation:

https://epa-prgs.ornl.gov/cgi-bin/chemicals/csl_search

Also note that, in addition to screening levels for direct exposure to soils (i.e., the Residential and Industrial Regional Screening Levels), the USEPA *Regional Screening Levels for Chemical Contaminants at Superfund Sites* provides tabulated "Protection of Groundwater" soil screening levels (SSLs) that are calculated using the Soil-Water Partition Equation:

https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

When using the RSL Calculator or the tabulated Protection of Groundwater SSLs, it is important to ensure that the input values used in the Soil-Water Partition Equation calculation, such as the dilution attenuation factor (DAF) and the acceptable groundwater concentration, are appropriate for use at the site. For example, the tabulated Protection of Groundwater SSLs are generated using a DAF of 1 and acceptable groundwater concentrations of either the MCLs or risk-based drinking water concentrations at a cancer risk of 1E-6 and hazard quotients of 0.1 or 1. These values may or may not be appropriate for use at your site.

3.1   Introduction to the Soil-Water Partition Equation

The Soil-Water Partition Equation is presented as (USEPA 1996a):

$$C_t = C_w \left(K_d + \frac{\theta_w + \theta_a H'}{\rho_b} \right) \qquad \text{(Equation 1)}$$

Table 2: Parameters for Equation 1 (continued on next page).

Parameter	Definition	Units	Default	Comment
C_t	soil screening level concentration (may be used as an acceptable soil concentration)	mg/kg	---	---
C_w	target soil leachate concentration	mg/L	---	see Step 2 (Section 3.2)
K_d	soil-water partition coefficient	L/kg	chemical-specific	see Step 3 (Section 3.2) default for organics: $K_d = K_{oc} \times f_{oc}$ default for inorganics: EPA RSL Tables
K_{oc}	soil organic carbon-water partition coefficient	L/kg	chemical-specific	see Step 3 (Section 3.2)
f_{oc}	fraction organic carbon in soil	kg/kg	0.002	see Step 4 (Section 3.2)

Parameter	Definition	Units	Default	Comment
θ_w	water-filled soil porosity	L_{water}/L_{soil}	0.3	---
θ_a	air-filled soil porosity	L_{air}/L_{soil}	0.13	$\theta_a = \eta - \theta_w$
η	total soil porosity	L_{pore}/L_{soil}	0.43	$\eta = 1 - \rho_b/\rho_s$
ρ_b	dry soil bulk density	kg/L	1.5	---
ρ_s	soil particle density	kg/L	2.65	---
H'	dimensionless Henry's Law Constant	unitless	chemical-specific	see Step 4 (Section 3.2)

The Soil-Water Partition Equation is a screening level model used to determine an acceptable contaminant concentration in soil based on the acceptable contaminant concentration in groundwater. The acceptable groundwater concentration is typically the groundwater cleanup standard for the site. Two fundamental processes are accounted for in the Soil-Water Partition Equation: 1) partitioning of the contaminant between soil particles, pore air, and pore water (leachate) and 2) leachate dilution in groundwater. The acceptable groundwater concentration is used to determine the target soil leachate concentration (C_w). The target soil leachate concentration is the maximum leachate concentration that, after dilution in groundwater, will not cause the groundwater concentration to exceed the acceptable level. The target soil leachate concentration is then used in the Soil-Water Partition Equation to determine the associated soil concentration due to soil-water partitioning.

When using the Soil-Water Partition Equation, the assumptions upon which the equation is based should be considered to determine if they are appropriate for site conditions. The following assumptions used in the Soil-Water Partition Equation are presented in the *Soil Screening Guidance: Technical Background Document* (USEPA 1996b):

- The source is infinite (i.e., steady-state concentrations will be maintained in groundwater over the exposure period of interest).

- Contaminants are uniformly distributed throughout the zone of contamination.

- Soil contamination extends from the surface to the water table (i.e., adsorption sites are filled in the unsaturated zone beneath the area of contamination).

- There is no chemical or biological degradation in the unsaturated zone.

- Equilibrium soil/water partitioning is instantaneous and linear in the contaminated soil.

- The receptor well is at the edge of the source (i.e., there is no dilution from recharge downgradient of the site) and is screened in the plume.

- The aquifer is unconsolidated and unconfined (surficial).

- Aquifer properties are homogeneous and isotropic.

- There is no attenuation (i.e. adsorption or degradation) of contaminants in the aquifer.

- Non-aqueous phase liquids (NAPLs) are not present at the site.

It is highly recommended that users of the Soil-Water Partition Equation review relevant sections of the *Soil Screening Guidance*, which includes the *User's Guide*, the *Technical Background Document*, and the *Supplemental Guidance for Developing Soil Screening Levels at Superfund Sites* (USEPA 1996a, 1996b, 2002). These documents are available at the following website:

https://www.epa.gov/superfund/superfund-soil-screening-guidance

3.2 Steps to Using the Soil-Water Partition Equation

The following methodology is recommended for using the Soil-Water Partition Equation to evaluate the soil-to-groundwater migration pathway:

1. Delineate the source area

   The source area (i.e., extent of contamination) is generally delineated based on program-specific criteria. Delineation criteria may include background concentrations, practical quantitation limits, residential Risk Reduction Standards, or other values approved by EPD. Contact the regulatory program overseeing the site investigation for information on applicable delineation criteria.

2. Determine the target soil leachate concentration, C_w

   Determination of the target soil leachate concentration is discussed in Section A.1 of the Appendix.

3. Determine the soil-water partition coefficient, K_d

   Literature values or site-specific values may be used for K_d. Section A.3 of the Appendix discusses the determination of literature-based and site-specific K_d values for both organic and inorganic compounds. For organic compounds, see Sections A.3.1 and A.3.3 of the Appendix. For inorganic compounds, see Sections A.3.2 and A.3.3 of the Appendix.

4. Determine other parameters

   a. Fraction organic carbon in soil, f_{oc}

      The default f_{oc} value for use in the Soil-Water Partition Equation is 0.002 kg/kg. A site-specific value may also be used. Determination of a site-specific value for f_{oc} is discussed in Section A.4 of the Appendix.

   b. Dimensionless Henry's Law Constant, H'

      Values for the dimensionless Henry's Law Constant should be taken from the most recent version of the USEPA Regional Screening Levels for Chemical Contaminants at Superfund Sites, Chemical Specific Parameters Table, which is available at:

      https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

      The dimensionless Henry's Law Constant should not be confused with the Henry's Law Constant, which has units of atm·m^3/mol. Note that when the dimensionless Henry's Law Constant is not available, as is the case for most inorganics, H' should be set to zero.

    c. Porosity [total (η), water-filled (θ_w), and air-filled (θ_a)]

The default values for total, water-filled, and air-filled porosity are 0.43, 0.3, and 0.13, respectively. These values may be adjusted based on site-specific geotechnical data.

    d. Dry soil bulk density, ρ_b

The default value for dry soil bulk density is 1.5 kg/L. This value may be adjusted based on site-specific geotechnical data.

5. Calculate the acceptable soil concentration, C_t

Once values for all parameters have been identified, the Soil-Water Partition Equation (refer to Equation 1) is used to calculate the acceptable soil concentration, which is considered a conservative estimate of the maximum contaminant concentration in soil that will not result in an exceedance of the acceptable groundwater concentration.

Note that the acceptable soil concentration determined using this or other methods in this document should not exceed the soil saturation limit (C_{sat}). Contaminants may be present in free phase when concentrations exceed C_{sat}. Default values for C_{sat} are listed in the USEPA RSL Tables and values may also be calculated. For more information, see Section 2.5.2 of the USEPA *Soil Screening Guidance: User's Guide* (USEPA 1996a).

4. What laboratory leaching tests are acceptable for evaluating the soil-to-groundwater migration pathway?

Two USEPA laboratory tests, the Toxicity Characteristic Leaching Procedure (TCLP, SW-846 Method 1311) and the Synthetic Precipitation Leaching Procedure (SPLP, SW-846 Method 1312), are generally accepted as stand-alone tests for evaluating the soil-to-groundwater migration pathway. These tests simulate leaching in soil samples, allowing a correlation to be made between the total contaminant concentration in a soil sample and the resulting leachate concentration. These tests are similar, but they use different extraction fluids to simulate different types of environmental conditions. The TCLP test was developed as a waste characterization test to assess the leaching of contaminants in a municipal solid waste landfill (USEPA 1996a). To simulate the conditions present in a municipal solid waste landfill, the TCLP test employs a buffered organic acid as the extraction fluid (TNRCC 1998).

The SPLP test employs a non-buffered inorganic extraction fluid that is intended to simulate leaching in typical soil, where pore water is present due to infiltration from precipitation (TNRCC 1998). For evaluating the soil-to-groundwater migration pathway, the use of the TCLP test should be limited to sites where conditions reflect those of a municipal solid waste landfill. The TCLP test remains the sole test for evaluating the toxicity characteristic for waste determination (i.e., solid vs. hazardous waste) purposes. *The SPLP test better simulates the field conditions at most regulated sites (other than municipal solid waste landfills), and therefore is the preferred laboratory leaching test for evaluating the soil-to-groundwater migration pathway.* Where allowable under applicable statutes and regulations, the SPLP Extraction Fluid #2 for "west of the Mississippi River" (pH = 5) may be used based on recent trends in the pH of Georgia precipitation (NADP 2019). Contact EPD prior to deviating from the SW-846 approved method. Other leaching tests may be considered on a site-specific basis.

5. What are the sample collection and reporting recommendations associated with the SPLP and TCLP tests?

5.1 Sample Collection Recommendations

1. For general soil sampling information, refer to the most recent version of the USEPA Region 4 Science and Ecosystem Support Division (SESD) *Soil Sampling Operating Procedure*, which is available at:

   https://www.epa.gov/quality/soil-sampling

2. The number of samples needed to adequately support the estimation of soil leaching thresholds using laboratory leaching tests will depend on the size and complexity of the site, as well as the method selected to evaluate the leaching test data.

   Generally, sites with larger source areas and/or a greater degree of subsurface heterogeneity will require more samples to remain adequately representative of spatial contaminant concentration variability and differences in leaching potential due to soil properties where more than one major soil type is present.

   In order to generate a data set that is more likely to support the requirements of the methods presented in this guidance, EPD generally recommends that a minimum of ten (10) samples be collected and analyzed per source area. However, depending on site-specific factors such as the size of the source area, fewer samples may be acceptable to EPD. If more rigorous statistical methods or models are used to evaluate leaching test results, the number of samples collected should be commensurate with the requirements of the model, at the desired level of confidence. Contact the EPD regulatory program overseeing the site investigation with questions regarding the number of samples needed at a particular site.

3. Each soil sample collected for leaching analysis should comprise one (1) aliquot for total concentration analysis and one (1) aliquot for the leaching procedure. An additional aliquot should be collected for the purpose of pH measurement for samples that are to be analyzed for inorganics or ionizing organics.

4. Soil samples should be collected across the range of contaminant concentrations (including higher, mid-range, and lower concentrations) found throughout the volume of soil within the source area to increase the likelihood of bracketing the target soil leachate concentration. Bracketing the target soil leachate concentration is necessary for determining the acceptable soil concentration, as further discussed in Question 6.

5. Soil samples should be collected from each major soil type and/or soil horizon found in the source area to assess differences in leaching potential due to soil properties.

6. Sampling Considerations for Inorganics and Semi-volatiles:
   a. Samples collected for inorganics or semi-volatiles analysis should be thoroughly homogenized to ensure that the aliquot used for totals analysis and the aliquot used for the leachate procedure are representative of the same sample matrix.

b. At least one duplicate totals aliquot should be collected and analyzed. The totals aliquot and the duplicate totals aliquot should be taken from the same homogenized soil sample. For more information regarding quality control sampling, see the most recent version of the USEPA Region 4 SESD *Field Sampling Quality Control Operating Procedure*, which is available at:

https://www.epa.gov/quality/field-sampling-quality-control

7. Sampling Consideration for Volatiles:

a. Soil samples for volatiles analysis should not be homogenized due to the potential for volatile loss. Since the individual aliquots must be collected and containerized separately (See SESD soil sampling protocol), care should be taken to collect the aliquot for totals analysis as close to the aliquot for the leaching procedure as practicable, so that they are as representative of similar soil conditions as possible.

b. Field chemical preservatives should not be used when collecting the aliquot to be used for the leaching procedure. These preservatives can cause contaminants to leach from soil, which can lead to inaccurate laboratory leaching test results. The leaching test aliquot should be collected in a laboratory-approved container (e.g., En Core® sampler). Care should be taken to minimize voids and completely fill the container (zero headspace). For consistency, it is recommended that the aliquots for totals analysis also be collected using methods that do not require field chemical preservatives.

c. At least one duplicate totals aliquot should be collected and analyzed. The duplicate totals aliquot should be collected as close as possible to the location of the totals aliquot of the original sample. As indicated above, additional information regarding sampling quality control can be found at:

https://www.epa.gov/quality/field-sampling-quality-control

5.2   Reporting Recommendations

The following should be reported when using SPLP or TCLP tests to evaluate the soil-to-groundwater migration pathway:

1. A narrative description of sampling and test methods

2. Laboratory analytical data

3. A site map (with scale), showing the location of each soil sample

4. A table, listing the following information for each soil sample:

a. Sample identification;

b. Depth of the soil sample;

c. Soil classification (i.e. silty sand, clay, etc.);

d. Soil pH (only needed for inorganics and ionizing organics);

e. Total contaminant concentration in soil (dry-weight basis) (mg/kg);

f. Leachate concentration (mg/L);

    g.   Volume of leachate (L);

    h.   Dry weight of soil used for leaching test (kg); and

    i.   Leachate pH.

Note: Consider consulting with the laboratory prior to submitting soil samples for analysis to ensure that the desired information will be reported.

6. I performed SPLP or TCLP tests to evaluate the soil-to-groundwater migration pathway. How do I analyze the test results?

The following methodology is recommended for analyzing SPLP or TCLP results to evaluate the soil-to-groundwater migration pathway. This methodology has been adapted from the New Jersey Department of Environmental Protection (NJDEP) document, *Development of Site-Specific Impact to Ground Water Soil Remediation Standards Using the Synthetic Precipitation Leaching Procedure* (NJDEP 2013):

1. Delineate the source area: Source area delineation is discussed in Section 3.2.

2. Determine the target soil leachate concentration: Determination of the target soil leachate concentration is discussed in Section A.1 of the Appendix.

3. Calculate the soil-water partition coefficient, K_d, for each leaching test: The lowest K_d value can generally be used as a conservative estimate of K_d. The calculation of K_d for a leaching test, and the methods of determining the final K_d value, are discussed in Section A.3.3.2 of the Appendix.

4. Estimate the field leachate concentration for each leaching test: The field leachate concentration can be estimated using the following equation:

$$C_L = \frac{C_T}{K_d + \frac{\theta_w + \theta_a H'}{\rho_b}} \qquad \text{(Equation 2)}$$

Table 3: Parameters for Equation 2 (continued on next page).

Parameter	Definition	Units	Default
C_L	field leachate concentration	mg/L	---
C_T	total contaminant concentration in soil	mg/kg	---
K_d	soil-water partition coefficient	L/kg	chemical-specific, $K_d = K_{oc} \times f_{oc}$ (organics)
K_{oc}	soil organic carbon-water partition coefficient	L/kg	chemical-specific
f_{oc}	fraction organic carbon in soil	kg/kg	0.002
θ_w	water-filled soil porosity	L_{water}/L_{soil}	0.3
θ_a	air-filled soil porosity	L_{air}/L_{soil}	0.13
ρ_b	dry soil bulk density	kg/L	1.5

Parameter	Definition	Units	Default
H′	dimensionless Henry's Law Constant	unitless	chemical-specific

5. Determine the acceptable soil concentration

   Three methods are presented that allow for the determination of the acceptable soil concentration. Methods 1 and 2 can be used to directly determine the acceptable soil concentration. Method 3 involves using a site-specific soil-water partition coefficient, K_d, in a fate and transport model to determine the acceptable soil concentration. Any of these methods may be used, provided that consideration is given to the individual method recommendations.

   a. Method 1: Determine an Acceptable Soil Concentration by Direct Comparison

      This method allows for the determination of an acceptable soil concentration by direct comparison of field leachate concentrations to the target soil leachate concentration. This method is described as follows:

      i. Prepare a table of total soil concentrations in ascending order with the corresponding field leachate concentration and the target soil leachate concentration.

      ii. If none of the field leachate concentrations exceed the target soil leachate concentration, the highest total soil concentration may be used as the acceptable soil leaching concentration. In these cases, EPD may request additional sampling to confirm the leaching test results.

      iii. If some, but not all, of the field leachate concentrations exceed the target soil leachate concentration, the highest total soil concentration for which no lower field leachate concentration exceeds the target soil leachate concentration may be used as the acceptable soil concentration.

      iv. If all of the field leachate concentrations exceed the target soil leachate concentration, none of the soil concentrations should be used and additional sampling is recommended.

      The use of Method 1 is illustrated in the following example:

Table 4: Example of Method 1 (continued on next page).

sample identification	total contaminant concentration in soil (mg/kg)	field leachate concentration (mg/L)	target soil leachate concentration (mg/L)
Sample 1	0.5	0.04	0.1
Sample 2	0.8	0.04	0.1
Sample 3	2	0.002	0.1
Sample 4	12	0.03	0.1
Sample 5	30	0.09	0.1
Sample 6	75	0.3	0.1
Sample 7	120	0.2	0.1
Sample 8	150	0.08	0.1

sample identification	total contaminant concentration in soil (mg/kg)	field leachate concentration (mg/L)	target soil leachate concentration (mg/L)
Sample 9	180	0.5	0.1
Sample 10	300	2	0.1

In this example, the acceptable soil concentration would be 30 mg/kg because the field leachate concentrations of this and all lower total soil concentrations are below the target soil leachate concentration. Note that even though the field leachate concentration of Sample 8 is below the target soil leachate concentration, the field leachate concentrations of Samples 6 and 7 (with lower soil concentrations) exceed the target soil leachate concentration. Therefore, the total soil concentration of Sample 8 should not be used as the acceptable soil concentration.

b. Method 2: Determine an Acceptable Soil Concentration using Linear Regression

This method allows for the determination of an acceptable soil concentration by linear regression analysis of the leaching test results. This method is described as follows:

  i. Determine if the data qualify for this method:

   1. At least half of the total soil concentration data points should be at or above the midpoint of the range of total soil concentration values.

   2. The target soil leachate concentration should be within the range of field leachate concentrations.

  ii. Prepare a scatterplot of total contaminant concentration in soil (y-axis) versus field leachate concentration (x-axis) using a computer program such as Microsoft Excel®. Apply a linear trend line to the data and display the trend line equation and the coefficient of determination (R^2) value on the graph, which measures how close the data are fitted to the trend line. If the R^2 value is 0.7 or greater, continue to the next step. If the R^2 value is less than 0.7, a different method such as Method 1, is recommended to determine the acceptable soil concentration.

  iii. The acceptable soil concentration may be determined using the following equation:

$$C_t = m(C_w) + b \qquad \text{(Equation 3)}$$

Table 5: Parameters for Equation 3.

Parameter	Definition	Units
C_t	acceptable soil concentration	mg/kg
C_w	target soil leachate concentration	mg/L
b	y-intercept of the linear trend line	mg/kg
m	slope of the linear trend line	L/kg

The use of Method 2 is illustrated in the following example:

Table 6: Example data for Method 2.

sample identification	total contaminant concentration in soil (mg/kg)	field leachate concentration (mg/L)	target soil leachate concentration (mg/L)
Sample 1	20	0.01	0.2
Sample 2	40	0.02	0.2
Sample 3	75	0.12	0.2
Sample 4	100	0.06	0.2
Sample 5	120	0.23	0.2
Sample 6	170	0.2	0.2
Sample 7	215	0.45	0.2
Sample 8	185	0.28	0.2
Sample 9	250	0.35	0.2
Sample 10	300	0.5	0.2

Note that half of the total soil concentrations are above the midpoint of the range of soil concentrations (160 mg/kg) and the target soil leachate concentration is within the range of field leachate concentrations. These are recommended conditions to proceed to the next step. The data are placed on a scatterplot, a linear trend line is applied, and the trend line equation and the R^2 value are displayed on the graph:
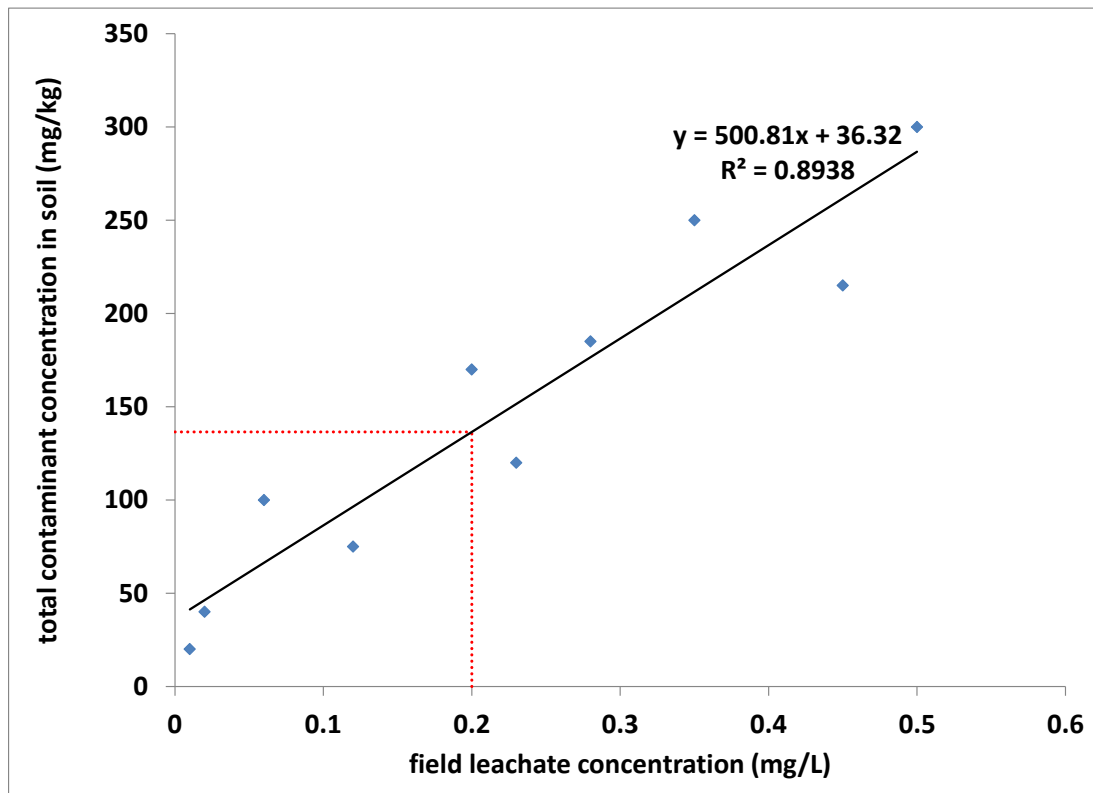

Figure 2: Example scatterplot for Method 2.

The R^2 value is greater than 0.7, so we can proceed to the next step. Plugging in the appropriate values to Equation 3 gives:

$$C_t = 500.81(0.2) + 36.32 = 136.48\frac{mg}{kg}$$

In this example, the acceptable soil concentration would be 136.48 mg/kg.

c. Method 3: Use a Site-Specific K_d in a Fate and Transport Model

Determination of a site-specific K_d from SPLP or TCLP results is discussed in Section A.3.3.2 of the Appendix. The use of other leaching tests to determine K_d may be considered. A site-specific K_d can be used as an input parameter in the Soil-Water Partition Equation (Equation 1) or in a more advanced fate and transport model.

7. What fate and transport models are acceptable for evaluating the soil-to-groundwater migration pathway?

Fate and transport models capable of evaluating the soil-to-groundwater migration pathway range from simple, such as the Soil-Water Partition Equation, to more advanced computer programs. Advantages of more advanced models include the ability to more accurately model site conditions, such as contaminant distribution and soil property variability, and the ability to consider more complex fate and transport processes, such as contaminant attenuation and degradation. EPD generally accepts models that are accepted or supported by the USEPA or the USGS and using the most probable representative values for model parameters. Other models may be accepted on a case-by-case basis. EPD encourages the use of public domain models that have been subject to extensive peer review. Some examples of public domain vadose zone models include SESOIL, VLEACH, and VS2DT.

The USEPA Mass Limit Equation accounts for more site-specific factors (e.g., depth of soil contamination) than the Soil-Water Partition Equation but does not require the use of a more advanced computer program. The USEPA Mass Limit Equation is presented as Equation 14 of the USEPA *Soil Screening Guidance: User's Guide* (USEPA 1996a). As with the Soil-Water Partition Equation, results of the Mass Limit Equation can be calculated using the USEPA RSL Calculator.

When using a fate and transport model to evaluate the soil-to-groundwater migration pathway, at a minimum, a vadose zone model should be used to show that leachate concentrations reaching groundwater will not exceed the acceptable groundwater concentration. Vadose zone models may be used in conjunction with groundwater models to account for contaminant dilution and attenuation in groundwater. Some cases may require the use of both vadose zone and groundwater models, such as when the potential for contaminant migration to a particular receptor well is being assessed.

Conservative parameters should be used in cases where reliable site-specific parameters are not available. EPD may require calibration of model parameters and field validation of model projections.

8. How are measured soil concentrations compared to calculated soil concentrations protective of the soil-to-groundwater migration pathway to demonstrate compliance?

The typical approach is to compare the maximum measured soil concentration from discrete soil samples to a calculated value that is protective of the soil-to-groundwater migration pathway (i.e., an acceptable soil concentration). If the maximum concentration is less than or equal to the calculated value, the soil would be considered protective of the soil-to-groundwater migration pathway.

The USEPA *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites* (USEPA 2002) describes two other methods for comparing measured site soil concentrations to calculated concentrations that are protective of the soil-to-groundwater migration pathway. These methods should be discussed with EPD prior to implementation, as they involve additional considerations such as source area definition and greater focus on Data Quality Objectives:

a. Using the mean concentration in soil borings:

   When sufficient discrete soil sample results are available from multiple depths within a borehole, the mean concentration of each contaminant of concern from the extent of contamination within the borehole may be compared to calculated values protective of the soil-to-groundwater migration pathway. It is recommended that USEPA Data Quality Objectives for subsurface soils, as presented in Section 2.3.3 of the *Soil Screening Guidance: User's Guide*, be reviewed to ensure that sufficient data is available to use this method. USEPA (1996a) states that "source areas" are the decision units for subsurface soils, and that a source area is defined by the horizontal and vertical extent of contamination. Therefore, soil samples used to calculate the mean should be collected from within the extent of contamination. Contamination delineation criteria may include background concentrations, practical quantitation limits, residential Risk Reduction Standards, or other values approved by EPD. Contact the EPD regulatory program overseeing the site investigation for information on applicable delineation criteria and data to be used to represent the "source area." This method should be discussed with EPD prior to implementation.

b. Using a 95% upper confidence limit (UCL) of the mean:

   If sufficient data is available, a 95% UCL of the mean contaminant soil concentration within the source area may be compared to a calculated value protective of the soil-to-groundwater migration pathway. As with averaging within soil borings, samples collected outside the source area should not be included in the calculation of the 95% UCL of the mean. USEPA (2002) notes that the standard Data Quality Objectives sampling approach will not yield sufficient data for calculating a 95% UCL of the mean concentration in subsurface soil. This method should be discussed with EPD prior to implementation.

9. What additional lines of evidence can be used to support an evaluation of the soil-to-groundwater migration pathway?

Users of this guidance are generally expected to evaluate the potential for soil leaching based on a comparison of measured contaminant concentrations in site soils to calculated soil concentrations protective of the soil-to-groundwater migration pathway developed consistent with USEPA guidance or an EPD-approved method. However, EPD recognizes that these quantitative methods may not account for all factors with the potential to influence the soil-to-groundwater migration pathway at a particular site. In cases where the soil release occurred many years ago and groundwater has not been impacted by soil leaching to groundwater, EPD may consider the use of these and other lines of evidence to demonstrate that the existing soil concentrations are protective of groundwater on a case-by-case basis. These lines of evidence may include, but are not limited to:

- Contaminant fate and transport characteristics (e.g., mobility)

- Age of the release: The age of the soil release should be on the order of decades old (since the last active release), such that the effect of any expected leaching to groundwater would be observable in downgradient groundwater. This is a critical line of evidence for using this method.

- Groundwater concentration trends: Sufficient groundwater data should demonstrate that groundwater has not been impacted by leaching. This is a critical line of evidence for using this method. In some cases, ongoing groundwater monitoring may be appropriate to confirm that the soil concentrations remain protective of groundwater.

- Magnitude of the release: consideration of the magnitude of soil contaminant concentrations that exceed calculated soil concentrations protective of the soil-to-groundwater migration pathway

- Horizontal and vertical extent of the release: consideration of the extent of the soil release, including the frequency of soil contaminant concentrations that exceed calculated soil concentrations protective of the soil-to-groundwater migration pathway

- Depth of groundwater: consideration of the depth of groundwater in relation to soil contamination

- Ground cover: consideration of how past ground cover (e.g., paved surface) may have influenced past leaching and how current/future soil cover may influence future leaching

- Area groundwater uses: consideration of groundwater uses in the surrounding area

References

Indiana Department of Environmental Management (IDEM). 2007. Determining the Fraction of Organic Carbon. OLQ-General ID-0119. September.
https://semspub.epa.gov/work/05/424375.pdf

National Atmospheric Deposition Program (NADP). 2019. National Trends Network, Animated pH Maps. Accessed August 1, 2019. http://nadp.slh.wisc.edu/maplib/ani/pH_ani.pdf

NJDEP. 2013. Development of Site-Specific Impact to Ground Water Soil Remediation Standards Using the Synthetic Precipitation Leaching Procedure. Version 3.0. November.
http://www.nj.gov/dep/srp/guidance/rs/splp_guidance.pdf

Ohio EPA. 2008a. Voluntary Action Program Derived Leach-Based Soil Values. Technical Guidance Document. Revision 3. October.
http://www.epa.state.oh.us/portals/30/vap/docs/sec-g-att.pdf

Ohio EPA. 2008b. Voluntary Action Program Derived Leach-Based Soil Values. Appendix Technical Support Document. October. Revision 3.
http://www.epa.state.oh.us/portals/30/vap/docs/sec-g-attapp.pdf

Texas Natural Resource Conservation Commission (TNRCC). 1998. When to use Toxicity Characteristic Leaching Procedure (TCLP) Test or Synthetic Precipitation Leaching Procedure (SPLP) Test to demonstrate the leaching potential of contaminants. Interoffice Memorandum. October. https://www.tceq.texas.gov/assets/public/remediation/trrp/tclpsplp.pdf

USEPA. 1987. DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings. USEPA Publication 600287035.
http://nepis.epa.gov/Simple.html

USEPA. 1996a. Soil Screening Guidance: User's Guide. USEPA Publication 9355.4-23. July.
https://www.epa.gov/superfund/superfund-soil-screening-guidance

USEPA. 1996b. Soil Screening Guidance: Technical Background Document. USEPA Publication EPA/540/R95/128. May.
https://www.epa.gov/superfund/superfund-soil-screening-guidance

USEPA. 2002. Supplemental Guidance for Developing Soil Screening Levels at Superfund Sites. OSWER 9355.4-24. December.
https://www.epa.gov/superfund/superfund-soil-screening-guidance

USEPA. Field Sampling Quality Control Operating Procedure. Region 4 Science and Ecosystem Support Division. As Amended.
https://www.epa.gov/quality/field-sampling-quality-control

USEPA. Soil Sampling Operating Procedure. Region 4 Science and Ecosystem Support Division. As Amended.
https://www.epa.gov/quality/soil-sampling

USEPA. Regional Screening Levels for Chemical Contaminants at Superfund Sites. Generic Tables. As Amended. https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

USEPA. Regional Screening Levels for Chemical Contaminants at Superfund Sites. User's Guide. As Amended. https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide

Washington Administrative Code (WAC). 2018. Deriving soil concentrations for groundwater protection. Section 173-340-747. http://apps.leg.wa.gov/wac/default.aspx?cite=173-340-747

Appendix

A.1   Determining the Target Soil Leachate Concentration

There are two cases to consider when determining the target soil leachate concentration:

1. The contaminant is not present in groundwater upgradient of the source area, and

2. The contaminant is present in groundwater upgradient of the source area.

In both cases, the target soil leachate concentration should not exceed the water solubility of the contaminant.

A.1.1   Case 1: The Contaminant is Not Present in Upgradient Groundwater

If groundwater upgradient of the source area has not been impacted by the contaminant, the target soil leachate concentration is calculated by multiplying the acceptable groundwater concentration by the dilution attenuation factor ("DAF") (USEPA 1996a):

$$C_w = C_f \times DAF \qquad \text{(Equation 4)}$$

Table 7: Parameters for Equation 4.

Parameter	Definition	Units
C_w	target soil leachate concentration	mg/L
C_f	acceptable groundwater concentration	mg/L
DAF	dilution attenuation factor	unitless

A.1.1.1   Determining DAF Values

The DAF is defined as "the ratio of contaminant concentration in soil leachate to the concentration in groundwater at the receptor point" (USEPA 1996b). The DAF quantifies the reduction in the contaminant concentration from soil leachate to the receptor point due to physical, chemical, and biological processes (USEPA 1996a). DAF values may be determined using either default values or by calculating a site-specific value.

A.1.1.1.1   Default DAF Values

A default DAF of 20 may be used in most cases when the source area is 0.5 acre or less and upgradient groundwater has not been impacted. However, EPD may not approve the use of a default DAF of 20 if site conditions indicate that it is not appropriate. Conditions where a default DAF of 20 may not be appropriate include fractured bedrock and karst aquifers (USEPA 1996b). For soil source areas greater than 0.5 acre, a default DAF of 1 may be used, or a site-specific DAF may be calculated.

A.1.1.1.2 Calculating a Site-Specific DAF

A site-specific DAF may be calculated using the following relationships (USEPA 1996a):

$$DAF = 1 + \frac{Kid}{LI} \qquad \text{(Equation 5)}$$

where:

$$d = \left(0.0112 \cdot L^2\right)^{0.5} + d_a\left[1 - \exp\left(\frac{-LI}{Kid_a}\right)\right] \qquad \text{(Equation 6)}$$

Table 8: Parameters for Equations 5 and 6.

Parameter	Definition	Units
DAF	dilution attenuation factor	unitless
K	hydraulic conductivity	ft/yr
i	hydraulic gradient	unitless
I	infiltration rate (groundwater recharge rate)	ft/yr
d	mixing zone depth (cannot exceed d_a)	ft
L	source length parallel to groundwater flow	ft
d_a	aquifer thickness	ft

The dilution attenuation factor calculated using Equation 5 is based solely on leachate dilution in groundwater and does not consider the effects of any other attenuation mechanisms. Note that the mixing zone depth (d) cannot be greater than the aquifer thickness (d_a). Equation 5 is appropriate for determining the DAF by which "concentrations are reduced when leachate mixes with a clean aquifer" (USEPA 2002).

A.1.2 Case 2: The Contaminant is Present in Upgradient Groundwater

If the contaminant is present in upgradient groundwater, the target soil leachate concentration may be calculated using Equation 4 with a DAF of 1 or using the Summers Model to account for the upgradient (background) contaminant concentration in the aquifer (Ohio EPA 2008a, 2008b). When expressed in terms of the parameters in Equation 5, the Summers Model can be presented as:

$$C_w = \left(1 + \frac{Kid}{LI}\right)C_f - \left(\frac{Kid}{LI}\right)C_i \qquad \text{(Equation 7)}$$

Table 9: Parameters for Equation 7.

Parameter	Definition	Units
C_w	target soil leachate concentration	mg/L
C_f	acceptable groundwater concentration	mg/L
C_i	upgradient groundwater concentration	mg/L
K	hydraulic conductivity	ft/yr
i	hydraulic gradient	unitless
I	infiltration rate (groundwater recharge rate)	ft/yr
d	mixing zone depth (see Equation 6)	ft
L	source length parallel to groundwater flow	ft

Note that when the upgradient groundwater concentration is zero, Equation 7 is equivalent to Equation 5.

A.2 Determining Groundwater Recharge Rates

Groundwater recharge rates may be estimated according to hydrogeologic setting using values from the USEPA publication, *DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings* (USEPA 1987). When a range of groundwater recharge rates is presented for a hydrogeologic setting, the maximum rate should be used to calculate a site-specific DAF. Note that the DRASTIC publication presents groundwater recharge rates in units of inches per year, which requires conversion to units of feet per year for use in Equations 5 - 7. Other methods to determine the groundwater recharge rate may also be considered.

A.3 Determining the Soil-Water Partition Coefficient, K_d

A.3.1 Determining K_d for Organics Using Literature Values

For organics only, K_d may be determined using the following relationship (USEPA 1996b):

$$K_d = K_{oc} \times f_{oc}$$ (Equation 8)

Table 10: Parameters for Equation 8.

Parameter	Definition	Units	Default
K_d	soil - water partition coefficient	L/kg	chemical-specific
K_{oc}	soil organic carbon - water partition coefficient	L/kg	chemical-specific
f_{oc}	fraction organic carbon in soil	kg/kg	0.002

Literature values of K_{oc} may be used in Equation 8 along with the default f_{oc} value of 0.002 to determine a literature-based value for K_d. It is recommended that literature values of K_{oc} be taken from the most recent version of the USEPA Regional Screening Levels for Chemical Contaminants at Superfund Sites, Chemical Specific Parameters Table, as the values provided therein are readily accessible and are updated regularly. The referenced table is available at:

https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

K_{oc} values from other sources may be considered if sufficient justification can be provided for their use.

It should be noted that K_{oc} values have been shown to vary as a function of pH for a class of organics known as ionizing organics. Ionizing organics include benzoic acid, 2-chlorophenol, 2,3-dichlorophenoxyacetic acid, 2,4-dichlorophenol, 2,4-dinitrophenol, pentachlorophenol, 2,3,4,5-tetrachlorophenol, 2,4,6-tetrachlorophenol, 2,4,5-trichlorophenol, and 2,4,6-trichlorophenol. Values of K_{oc} as a function of pH for ionizing organics are presented in Exhibit C-2 of the *Supplemental Guidance for Developing Soil Screening Levels at Superfund Sites* (USEPA 2002), which is available at:

https://semspub.epa.gov/work/HQ/174067.pdf

A.3.2   Determining K_d for Inorganics Using Literature Values

Literature values of K_d for selected inorganics are listed in the "Soil to Groundwater" section of the *USEPA Regional Screening Levels User's Guide*, which is available at:

https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide

These values should be used as defaults when relevant site-specific information (pH, SPLP data, etc.) is not available.

Literature values of K_d as a function of pH for selected inorganics are listed in Exhibit C-4 of the *Supplemental Guidance for Developing Soil Screening Levels at Superfund Sites* (USEPA 2002):

https://semspub.epa.gov/work/HQ/174067.pdf

The K_d value for inorganics can be affected by a variety of factors, including "pH, oxidation-reduction conditions, iron oxide content, soil organic matter content, cation exchange capacity, and major ion chemistry" (USEPA 1996b). Therefore, it is recommended that laboratory leaching tests be used when possible to evaluate the soil-to-groundwater migration pathway for inorganics, as described in Question 6, particularly when the subsurface pH has been altered by the properties of the chemical released (e.g., reduced pH caused by the release of an acid).

A.3.3   Determining a Site-Specific K_d

A.3.3.1   Determining a Site-Specific K_d for Organics Based on the Fraction Organic Carbon in Soil, f_{oc}

For organics, a site-specific K_d may be determined by multiplying a literature-based K_{oc} and a site-specific value for f_{oc} in Equation 8. Determination of a site-specific f_{oc} value is discussed in Section A.4 of the Appendix. A site-specific K_d value for organics may also be determined using a laboratory leaching test, as discussed in the following section (Section A.3.3.2).

A.3.3.2   Determining a Site-Specific K_d Using a Laboratory Leaching Test

A site-specific K_d for both organics and inorganics can be determined using a laboratory leaching test. For a description of laboratory leaching tests, sampling and reporting recommendations, and recommended data reduction, see Questions 4, 5, and 6.

This method allows for the determination of a site-specific soil-water partition coefficient, K_d, using leaching test results. The soil-water partition coefficient can be used in a fate and transport model such as the Soil-Water Partition Equation to determine an acceptable soil concentration. When linear partitioning is assumed, K_d is defined as (NJDEP 2013):

$$K_d = \frac{C_S}{C_L} \qquad \text{(Equation 9)}$$

Table 11: Parameters for Equation 9.

Parameter	Definition	Units
K_d	soil - water partition coefficient	L/kg
C_S	equilibrium contaminant concentration sorbed to soil	mg/kg
C_L	equilibrium contaminant concentration in leachate	mg/L

Using the results of a leaching test, a sample-specific K_d can be calculated using the following relationship (NJDEP 2013):

$$K_d = \frac{C_T M_S - C_{SPLP} V_L}{M_S C_{SPLP}} \qquad \text{(Equation 10)}$$

Table 12: Parameters for Equation 10.

Parameter	Definition	Units
K_d	soil - water partition coefficient	L/kg
C_{SPLP}	SPLP or TCLP leachate concentration	mg/L
V_L	volume of leachate	L
C_T	total contaminant soil concentration (prior to leaching test)	mg/kg
M_S	dry weight of soil used for leaching test	kg

The lowest calculated K_d value can generally be used as a conservative estimate of K_d for the source area. If statistical methods are considered to determine a representative K_d, it is recommended that consideration be given to the population distribution, the variance of the observed values, and the limitations of using small numbers of observations to conduct statistical analysis.

A.4 Determining the Fraction Organic Carbon in Soil, f_{oc}

The default value for f_{oc} is 0.002 kg/kg, or 0.2%. However, a site-specific f_{oc} may also be determined by measuring site-specific soil organic carbon. Sample collection, analytical methods, and reporting recommendations for soil organic carbon measurement are discussed in the following sections.

A.4.1 Sample Collection Recommendations

1. A minimum of ten (10) discrete soil samples should be collected. The total number of samples needed and the horizontal and vertical distribution of sample locations are dependent on the heterogeneity of the subsurface and should be evaluated on a site-specific basis.

2. When possible, samples should be collected at least two (2) feet below the ground surface (i.e., below the root zone) in uncontaminated soil that is representative of soil through which contaminants are likely to migrate (WAC 2018). Totals analysis, using the appropriate analytical method, for organic constituents of concern should be used to show that the soil used for organic carbon measurement has not been impacted by organic contaminants. Soil samples collected from surficial soils (where the greatest amount of organic carbon is typically located) or from soil impacted with organic contaminants may result in an overestimation of the ability of subsurface soil to adsorb contaminants.

A.4.2 Analytical Methods

The Modified Walkley-Black Method (dichromate oxidation) is the recommended method for measuring total organic carbon (TOC) in soil. Other methods may be considered on a site-specific basis. Note that ASTM D2974 provides a measurement of soil organic *matter* as opposed to soil organic carbon. For more information, see the Indiana Department of Environmental Management (IDEM) guidance document, *Determining the Fraction of Organic Carbon* (IDEM 2007).

A.4.3 Reporting Recommendations

1. A site map (with scale), showing the location of each soil sample

2. Laboratory analytical data

3. A narrative describing the sampling methods used

4. A table, listing the following information for each sample:

    a. Sample identification;

    b. Depth of the soil sample;

  c. Total soil contaminant concentration (mg/kg);

  d. Soil classification (i.e. silty sand, clay, etc.); and

  e. Total organic carbon in soil (dry weight basis) (mg/kg).

When soil TOC is reported in units of mg/kg, the fraction of organic carbon (kg/kg) is calculated using the following conversion:

$$f_{oc} = \frac{TOC}{10^6}$$
                     (Equation 11)

Table 13: Parameters for Equation 11.

Parameter	Definition	Units
f_{oc}	fraction organic carbon in soil	kg/kg
TOC	total organic carbon in soil	mg/kg

The lowest calculated f_{oc} value can generally be used as a conservative estimate of f_{oc} for the source area. However, if a sufficient number of samples have been collected, then the average f_{oc} value (e.g., 95% UCL of the mean) could also be used. If statistical methods are considered to determine a representative f_{oc}, it is recommended that consideration be given to the population distribution, the variance of the observed values, and the limitations of using small numbers of observations to conduct statistical analysis.