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SECTION IV. GENERAL GUIDANCE

A. Fate and Transport Analysis

Fate and transport analyses required under Act 2 may involve a wide spectrum of predictive assumptions, calculations and simulations, from the simple to the complex, depending on the hydrogeologic characteristics of a site, future use scenarios, and the selection/applicability of a particular cleanup standard.

Generally, fate and transport analyses under Act 2 may be used for the following purposes:

- To predict the concentrations of one or more contaminants at one or more locations in the future, often at a specific time (e.g., 10 years).

~~? To help determine site-specific groundwater characteristics,~~

~~? To locate areas of potential environmental concern, and~~

- To assess potential remediation alternatives.
- To evaluate natural attenuation ~~remedies~~ and associated monitoring requirements.
- To assure continued attainment of the relevant standard.
- To ~~validate~~ estimate groundwater chemical flux used in mass balance calculations for attainment of surface water standards.
- To assess post-remediation care requirements and termination.

Furthermore, fate and transport analysis is used in specific ways under the three standards.

BACKGROUND STANDARD

- ◆ To justify reduced duration for monitoring of upgradient release.
- ◆ To combine background groundwater standard with non-background soil standards.
- ◆ To assess the impact of transformations in the upgradient plume.

STATEWIDE HEALTH STANDARD

- ◆ To justify reduced duration of attainment monitoring at the point of compliance.
- ◆ To complete the equivalency demonstration for soil-to-groundwater attainment.
- ◆ To predict the extent of contamination above the standard in off-property non-use aquifers.

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- ◆ To demonstrate attainment of the used aquifer standard at a point 1,000 feet downgradient from the point of compliance for the non-use aquifer standard.
- ◆ To demonstrate compliance with surface water standards where there is diffuse groundwater flow to surface water.

SITE-SPECIFIC STANDARD

- ◆ To identify current completed pathways and related exposures.
- ◆ To predict future completed pathways and related exposures.
- ◆ To demonstrate pathway elimination.
- ◆ To establish numerical site-specific risk-based standards.
- ◆ To demonstrate compliance with surface water standards where there is diffuse groundwater flow to surface water.

In many cases, a Fate and transport analysis or modeling is a necessary part of site characterization and in demonstrating attainment of an Act 2 standard. However, the regulations governing Act 2 use the term “fate and transport analysis” as opposed to “fate and transport model.” This particular distinction was made because it will not always be necessary to run an analytical or numerical quantitative “fate and transport model” to achieve a standard.

Whether simple or complex, any fate and transport analysis must rely on having and/or obtaining valid data. Reliable field data will be critical in supporting the professional conclusions regarding any predictions of contaminant fate and transport and needs to be considered during the site characterization.

Fate and transport analysis will be used in the Act 2 process to predict contaminant concentrations migrating through the unsaturated zone and the saturated zone, including the impact of soil contamination on groundwater. It will also include an analysis of diffuse groundwater flow into surface water (e.g., a stream) for purposes of determining compliance with surface water quality standards.

When applicable, the fate and transport analysis should also consider the degradation of (a) particular chemical compound(s) into one or several “breakdown” compounds. This can occur in the unsaturated or saturated zone at or below the point of release of a particular compound of concern, or downgradient in the chemical plume. An example may include a scenario involving a release of trichloroethylene (TCE) from an upgradient source which has entered the saturated zone and migrated downgradient under a site

seeking a release under the background standard. The site in question may exhibit dichloroethylene (DCE) and vinyl chloride (VC) in wells on its property but also may have never used chlorinated compounds. In this case, the remediator may be able to demonstrate that there was no release of the regulated substance on the property and use fate and transport analysis to demonstrate that the constituents result from breakdown of compounds from the upgradient release.

1. Fate and Transport Analysis in the Unsaturated Zone

a) General

In lieu of using the soil-to-groundwater Medium-Specific Concentrations (MSCs) from Tables 3 and 4 in Appendix A of the Act 2 regulations as the Statewide health standards, a person may also perform a site-specific demonstration. The site-specific demonstration can be used to show that contaminant levels in soil exceeding the Statewide health standard for one or more contaminants at that site are protective of groundwater. Such a demonstration requires the use of fate and transport models, equations, algorithms, or methods (hereafter “analytical tools”) applied to contaminants in the soil of the unsaturated zone and may also include the use of groundwater fate and transport analytical tools (*e.g.*, using the results of an unsaturated zone transport demonstration as input into a groundwater fate and transport analysis).

The unsaturated zone fate and transport analytical tools may be very simple equations requiring minimal input or may be more complex models requiring much more detailed input. The choice of the analytical tool or tools used in making site-specific demonstrations for contaminants in unsaturated zone soil should be appropriate to the circumstances of the site. At a minimum, the analytical tools used in making demonstrations in the unsaturated zone should include certain contaminant-specific and site-specific parameters. Other parameters may also be necessary depending on the analytical tools being used and the overall goal of the demonstration. In addition, the analytical tools and parameter input values themselves are subject to certain conditions.

b) Minimum Contaminant-specific and Site-specific Requirements

With very few exceptions, the analytical tools currently available for unsaturated zone contaminant fate and transport demonstrations are based on equilibrium partitioning equations. The equations that have been used in estimating the soil-to-groundwater MSCs and the soil buffer distances in Tables 3 and 4 in Appendix A of the Act 2 regulations are equilibrium partitioning equations. These equations can be used in a variety of different types of

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analytical tools. Depending on the analytical tool being used, other parameter input values may be necessary. At a minimum, input values are needed for each of the following parameters for any unsaturated zone analytical tool:

i) Contaminant-specific Requirements for All Analytical Tools

- **K_{oc}** in L/kg or mL/g (for organic compounds only)-This is the organic carbon partition coefficient. Values for this parameter for listed organic regulated substances can be found in Table 5 in Appendix A of the Act 2 regulations or in the scientific literature. For organic compounds not listed in Appendix A of the Act 2 regulations, values can be found in the literature. K_{oc} estimation methods (based on other parameters such as aqueous solubility, octanol-water partition coefficient, bioconcentration factor, and molecular structure) are also available in the literature.
- **K_d** in L/kg or mL/g (primarily for inorganic contaminants and, in some instances, organic compounds)-This is the soil to water partition coefficient. Values for this parameter for listed inorganic regulated substances can be found in Table 5 in Appendix A of the Act 2 regulations. Some K_d values for inorganic contaminants can also be found in the scientific literature. In many instances, it may be necessary to estimate K_d values based on soil analytical data at a particular site. This can be done by using total contaminant concentrations in soil in conjunction with leachable concentrations. Generally, the K_d values for organic compounds are estimated from K_{oc} values and the fraction of organic carbon in soil (f_{oc} - which is discussed later). It is also possible to estimate K_d values for organics by using total contaminant concentrations in soil in conjunction with leachable concentrations. If K_d values are estimated in this manner, it is not necessary to include or use a K_{oc} value for the organic compound.
- **C_{soil}** in mg/kg-This is the dry weight concentration of regulated substance or contaminant in soil which is determined through use of the site characterization data (if the demonstration is being done to show that groundwater is protected under current site conditions) or which is used as input (on a trial and error basis) to estimate a concentration in soil that would be protective of groundwater.

ii) Site-specific Requirements for All Analytical Tools

- **P_w** (dimensionless)-This is the water-filled porosity of the unsaturated zone soil. Appropriate values for this parameter generally range from 0.05 to 0.15 for sandy soils to 0.26 to 0.45 for clays. A default value of 0.2 has been

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used in the estimation of the soil to groundwater MSCs in Tables 3 and 4 in Appendix A of the Act 2 regulations.

- Y_b in kg/L or g/mL-This is dry bulk density of unsaturated zone soil. Appropriate values for this parameter generally range from 1.3 to 2.0 for silts and clays to 1.6 to 2.2 for sandy soils to 1.8 to 2.3 for gravelly soils. A default value of 1.8 has been used in the estimation of the soil to groundwater MSCs in Tables 3 and 4 in Appendix A of the Act 2 regulations.
- f_{oc} (dimensionless)-This is the fraction of organic carbon in unsaturated zone soil. This parameter applies only to demonstrations being done for organic compounds where the K_{oc} values for the compounds are being used. For demonstrations for organic compounds where K_d is being estimated or determined by a means other than use of K_{oc} , this parameter is not needed. Typical values for this parameter range from 0.001 to 0.006 for subsurface soils to 0.01 to 0.03 for topsoils. A default value of 0.0025 has been used in the estimation of the soil to groundwater MSCs in Table 3 in Appendix A of the Act 2 regulations. A value of 0.005 has been used in estimation of the soil to groundwater buffer distances in Table 3 in Appendix A of the Act 2 regulations.

iii) Additional Requirements Depending on Type of Analytical Tool

The simplest unsaturated zone analytical tools are those that estimate contaminant concentrations in unsaturated zone soil pore water from equilibrium partitioning equations and then use those aqueous concentrations as source input into a groundwater fate and transport analysis. Actual transport through the unsaturated zone is not estimated with this type of analytical tool. This type of unsaturated zone analytical tool would require input data for only those parameters discussed above.

Another type of unsaturated zone analytical tool that is commonly used and which is more complex is one that estimates the migration of contaminants through the unsaturated zone. These are generally either infinite source or finite source analytical tools. Both are more complicated than the one previously discussed and, as such, require additional parameter input values. Both of these analytical tools require a water recharge rate so that a pore water velocity can be estimated and the vertical depth to groundwater or bedrock from the contaminated soil. An unsaturated zone finite source analytical tool is particularly useful in demonstrating how long it will take a contaminant to migrate from unsaturated zone soils to groundwater (if at all) and what the contaminant concentration (including the maximum concentration) will be in soil or soil pore water at various depths and at various times as migration

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occurs. Finite source models generally require input values for additional parameters such as values for C_{soil} at different depths from the surface of the unsaturated zone. This can ensure that mass balance constraints are met, *i.e.*, the analytical tool will not estimate migration of a greater mass of contaminant than the amount that was originally in the source soil.

In addition, more complex unsaturated zone analytical tools can take into account other mechanisms that would affect the vertical migration of contaminants toward groundwater. These mechanisms are generally ones that result in loss of the contaminant through time meaning that additional input values are required. Two loss mechanisms are biodegradation and volatilization. Analytical tools that consider biodegradation require either a degradation rate constant (in units of reciprocal time) or a half-life value (in units of time). Rarely, an analytical tool may consider loss from volatilization. This would require a volatilization rate constant which can be calculated from several other parameters (such as Henry's constant, vapor pressure, aqueous solubility, other partition coefficients as well as soil property data) or can be estimated using on-site analytical data.

c) Conditions for Use of Analytical Tools and Parameter Input Values

Dozens of unsaturated zone analytical tools exist in the public domain, most of which are based on equilibrium partitioning between the solid soil matrix and the soil pore water. As such, most of these analytical tools are very similar with respect to the parameters that require input values. In order to ensure validity of the results of all unsaturated zone demonstrations submitted to the department, the following conditions should be met:

- Analytical tools used for unsaturated zone transport demonstrations should be based on equilibrium partitioning concepts when possible. Although analytical tools based on other concepts (such as metal speciation and desorption non-equilibrium) exist and may be technically valid, their use could cause significant delays in department review time.
- The source of all values for all required input parameters (K_{oc} , K_d , C_{soil} , Π_w , Ψ_b , f_{oc}) should be provided. All data used as input for C_{soil} should be representative of the area for which the demonstration is being made and should meet all site characterization requirements.
- If analytical tools require input values for water recharge rate and vertical depth to groundwater, the sources of those values should be provided.
- Any degradation rate constant or half-life used in any unsaturated zone analytical tool should be based on site-specific data. Well-documented degradation constants and half-life values may be used from the literature

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or other studies only when it can be shown that the conditions at the site are clearly similar to those from which the degradation rate constant or half-life came. In addition, degradation products which may be toxic (such as those from chlorinated alkenes) should be considered in the demonstration. If these conditions are not met, the degradation rate constant should be assumed to be zero.

- Any unsaturated zone analytical tool that incorporates loss of contaminant from volatilization processes should base the volatilization rate constant on volatilization data for soils existing at the site. Otherwise, loss due to volatilization should be assumed to be zero.
- Any unsaturated zone analytical tool should be used only for soils in the unsaturated zone and should not be used for saturated zone soils or bedrock.
- For any unsaturated zone analytical tool that links to groundwater by means of dilution directly under the area of contaminated soil, the entire aquifer depth directly under the soil should not be used in dilution calculations, *i.e.*, as a mixing zone. The mixing zone should be calculated based on specific site parameters such as pore water velocity, groundwater velocity and direction, depth of the entire aquifer under the site, and areal extent of soil contamination.

d) Conclusion

This guidance is being provided to aid any person who is submitting results of a fate and transport analysis for the unsaturated zone to do so in a manner that will ensure validity of the analysis as well as timely and efficient review by the Department. There are many unsaturated zone analytical tools available in the public and private domains. Some of these are extremely complex, difficult to use, and not readily available to department staff while others are fairly simple, easy to use and are readily available to the department. For unsaturated zone fate and transport analysis submissions that rely on concepts other than equilibrium partitioning (such as metal speciation and non-equilibrium desorption), adequate supporting documentation must be submitted to the Department.

2. Fate and Transport Analysis in the Saturated Zone

This section provides guidelines for the application of fate and transport analysis in the saturated zone ~~as provided in Act 2~~. As stated above, a “fate and transport analysis” is not necessarily a highly complex computer simulation. It can be a range of analyses, based on physical, structural, chemical and hydraulic factors. It is based on professional judgment, and may need to include the use of simulations.

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Elements of Fate and Transport Analysis include:

GROUNDWATER FLOW

- Direction
- Velocity
- Boundaries

CHEMICAL FATE AND TRANSPORT MECHANISMS

- Leaching/dissolving
- Adsorption/desorption
- Matrix diffusion
- Degradation/transformations/reactions
- Volatilization
- Precipitation
- Phase behavior

Depending of the characteristics of the site and the type of standard/remediation selected, the fate and transport analysis can range from the simple to the complex, which can span from qualitative “empirical” or simple conceptual models, semi-quantitative and up to quantitative “empirical” conceptual models up to simulated-simulation (analytical and numerical) models.

Simple descriptive or conceptual “models” may be either qualitative or semi-quantitative. A particular example under this scenario might be a facility seeking a release under the background standard. This facility (facility “A”) is downgradient from facility “B,” which has caused a release of a contaminant to groundwater. The fate and transport analysis required under Section 250.204(f)(5) could conceivably be a simple qualitative demonstration of a site conceptual model which employs the use of monitoring well data/measurements to establish that facility “A” is clearly hydraulically downgradient of facility “B.” Data requirements would include water level measurements from a sufficient number of properly located monitoring wells and establishing the hydraulic gradient. Note, however, that simple scenarios such as this can easily become more complicated by other factors including water level fluctuations, pumping influences of wells, etc., which could require a more detailed quantitative fate and transport analysis.

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Another scenario could involve the use of simple extrapolation in predicting groundwater plume movement or its relative stability over time. If groundwater monitoring samples have been collected over a sufficiently long period of time, and the information is good, valid data, then certain predictions can be made using professional judgment as to aspects of plume behavior. For example, monitoring over a number of years may indicate that the contaminant plume has exhibited no movement over that time. In this case, the use of professional judgment involving simple extrapolation of the data may be a sufficient fate and transport analysis. The conclusion could be made, based on the above merits, that the plume has reached a steady state condition and would not migrate further downgradient.

~~Semi-Quantitative~~ ~~or quantitative~~ fate and transport analysis may be sufficient needed in slightly more complex situations, where a demonstration of attainment would require additional data and calculations. One example might be a facility seeking to demonstrate that very low groundwater velocities in bedrock would preclude contaminated groundwater from the facility from reaching the property boundary/POC. Data requirements in this case would need to include calculation of hydraulic gradient, determination of hydraulic conductivity, estimation/measurement of effective “porosity,” and calculation of groundwater velocity. Note that this somewhat simple example could evolve into a more detailed quantitative or simulated model given a variety of complicating factors, such as saturated flow in soil, preferential fracture flow, etc. Another example of this type may be a demonstration of groundwater discharge into a natural flow boundary, as in the case of a facility located adjacent to a large river sustained by regional groundwater discharge. While in some cases this might be a qualitative analysis, in other cases there would be a need to determine both vertical and horizontal gradients to demonstrate the stream is in fact a discharge feature and not losing flow to the surrounding terrain.

Quantitative analysis may involve the use of more complicated fate and transport tools involving various analytical equations up to the more complex numerical simulations of groundwater flow, which collectively can help determine the spread of contamination in a plume and predict its fate and concentration at specific future times and locations. The simpler analytical equations often do not require the use of a computer and are more appropriate where more uniform aquifer conditions exist and there are no complex boundary conditions. An example might be a facility seeking a release under Act 2 which is underlain by alluvium near a stream. Analytical fate and transport equations can be used to help determine the concentration of a groundwater contaminant at a downgradient location. In many cases the simple empirical examples mentioned above may need to employ analytical

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equations as conditions warrant, to account for dilution, attenuation, degradation, and other physical and chemical factors in contaminant fate and transport.

Numerical simulations are the most complex models used under the provisions of fate and transport analysis under Act 2. They generally require use of a digital computer due to the number of simultaneous equations to be solved. They are most applicable where predictions of groundwater contamination need to be made at certain locations in the future (*e.g.*, property boundary, 1000 feet downgradient from property boundary, etc.), at sites which exhibit more heterogeneous geologic/hydrogeologic characteristics and more complex boundary conditions (which are common in Pennsylvania). As such, they will be useful tools for a variety of sites where such predictions are required to demonstrate attainment of an Act 2 standard. Additional discussion on numerical models is provided below.

a) Groundwater Solute Fate and Transport Modeling (General)

The Department recommends that fate and transport analysis, especially if it involves more complex numerical models, be conducted by those with appropriate academic training and practical experience in the field.

Except in cases where it is unnecessary to project or predict contaminant concentrations in groundwater at various locations into the future, some sort of quantitative fate and transport analysis such as groundwater modeling will very likely be needed.

The following data are the minimum that should be derived from the site characterization for use in many models, although specific models may require more:

Source Geometry and Concentration

- Groundwater flow direction
- Hydraulic conductivity
- Hydraulic gradient
- Fraction of organic carbon (unless assumed to be 0.001 [default])

The following data can often be derived from literature values or estimated based on other site characteristics:

- Organic partition coefficient (Koc)
- First-order decay coefficient (lambda)
- Soil bulk density
- Porosity

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Readers are referred to ASTM Standard Guide D 5447-93 for an overview of the basic elements involved in groundwater flow modeling effort. The same general principles apply to fate and transport modeling. Since the ASTM Standard Guide 5447-93 is intended as a general guide, covering both analytical and numerical models, all elements discussed may not be applicable to every modeling situation.

b) Define Study Objectives

In all cases the site characterization should be conducted with the objective of providing the data necessary to demonstrate attainment of an Act 2 standard. Prior to any computer modeling, an initial conceptual model of local hydrogeologic conditions should be developed. The results of the site characterization/initial conceptual model will influence what kind of fate and transport model, if any, should be used, as well as many of the values for the input parameters to that model. Some models require certain kinds or quantities of data which is good to know ahead of time. To some extent this will be an iterative process. As data is collected and evaluated, the selected Act 2 remediation standard may change, and areas where additional data is needed may be identified.

The acceptable tolerances for model calibration should also be defined in the study objectives.

c) Data Collection

The data used for groundwater fate and transport modeling will come from the site characterization and, in some cases, values published in scientific literature or Table 5 in Appendix A to the Act 2 regulations. Examples of data that may need to be obtained from published values include first-order decay coefficients and equilibrium partitioning coefficients. Once obtained, these values may need to be adjusted within reasonable ranges to calibrate a model to site conditions. Examples of data which should be obtained from the site characterization, to name a few, include hydraulic conductivity, gradients, porosity, organic carbon content and chemical concentrations. Some parameters such as dispersion coefficients, which are not available from the literature or site characterization work, initially need to be estimated according to basic assumptions and then adjusted during model calibration to match actual plume shape and concentration data.

d) Conceptual Model

As stated in ASTM D 5447, “the purpose of the conceptual model is to consolidate site and regional hydrogeologic and hydrologic data into a set of assumptions and concepts that can be evaluated quantitatively.” The

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conceptual model of the site will emerge from the data collected during the site characterization. The site characterization work should be designed to assure that the quantity and kind of data collected will, in the end, be sufficient for justifying and completing the fate and transport analysis. Elements important to developing the conceptual model of the site for any fate and transport analysis include geologic, hydrologic, hydraulic and contaminant data (note that these are common elements of some of the non-numerical conceptual models discussed above). Data collection should be concentrated on the site, but off-site features that influence contaminant fate and transport on the site should not be overlooked.

i) Geologic Data

- thickness, continuity, lithology and structural features of consolidated geologic formations underlying the site;
- thickness, texture, density and organic carbon content of soil and unconsolidated units;
- information from review of published reports on the geology and soils of the site and nearby areas, or previous work at the site;
- information from any additional investigation needed to confirm or refine existing data such as wells, borings and backhoe pits, and possibly geophysical methods.

ii) Hydrologic Data

- water levels, hydraulic gradients and groundwater flow directions, including seasonal variations;
- the presence and magnitude of vertical gradients at the site;
- recharge and discharge boundaries relevant to the site including groundwater divides, streams, and drains;
- sources and sinks, *e.g.*, characteristics of any pumping or injection wells, artificial recharge, ponds, etc.;
- the presence of any confining units;
- for bedrock aquifers, the degree to which the aquifer system departs from assumptions regarding flow in porous media;
- data from review of available information as well as drilling of wells, borings and piezometers, and water level measurements over regular intervals.

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iii) Hydraulic Data

- hydraulic conductivity and transmissivity data for consolidated and unconsolidated deposits;
- porosity, effective porosity estimates, and storativity;
- the degree to which the aquifer(s) depart from assumptions of isotropy or homogeneity;
- the degree of interconnection between different aquifer units and leakage characteristics between different water-bearing units;
- hydraulic data often is not available at the level of detail necessary and may require pumping tests on wells to determine aquifer anisotropy of bedrock systems and values for other hydraulic parameters such as transmissivity. Slug tests and laboratory permeability tests may suffice for unconsolidated deposits.

iv) Chemical and Contaminant Data

- location, age and current status of source areas to the extent knowable;
- types of contaminants and their chemical properties such as viscosity, solubility, biodegradability, density, toxicity, Koc value, decay rate, etc.;
- the magnitude and vertical and horizontal extent of contamination in soil and/or groundwater;
- dissolved oxygen content and other electron acceptors in groundwater, if required by the model;
- historical plume configuration based on existing monitoring data;
- determination if the contaminant plume is at steady state conditions or is continuing to migrate. This is a critical piece of information. Is the mass of contamination increasing, decreasing or relatively constant? This should be determined by monitoring the vertical and horizontal extent of groundwater contamination for a period of time sufficient to reveal the trend. These data will be useful in calibrating the model and making predictive simulations. In some cases, the monitoring data alone may be all that is needed to complete the fate and transport analysis, provided the monitoring record is sufficiently long.
- review of chemicals used at the facility, which will help identify the chemicals of concern. Sampling soil, soil vapors and groundwater from appropriately constructed monitoring wells, borings or excavations and checking for any free product will need to be performed. Geophysical

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methods may be useful to delineate areas needing further investigation or identifying sources.

e) Code Selection

When the site characterization is completed and the conceptual model has been developed, selection of an appropriate computer code can be made. At sites where there is little variation in conditions over the model domain, with a simple plume geometry or conceptual model, relatively simple analytical models should be employed. At sites where the site characterization has determined significant variation in important parameters, or where more complex questions are being asked, a more sophisticated numerical solution may be needed.

The Department has prepared ~~two~~ three spreadsheets that may be useful in completing a fate and transport analysis. All spreadsheets are based on the

$$C(x, y, z, t) = \left(\frac{C_o}{8}\right) \exp\left\{\frac{x}{2a_x} \left[1 - \left(1 + 4I a_x / v\right)^{1/2}\right]\right\} \operatorname{erfc}\left\{\frac{x - vt(\sqrt{1 + 4I a_x / v})}{2\sqrt{a_x vt}}\right\} \\ \left\{\operatorname{erf}\left[\frac{(y + Y/2)}{2\sqrt{a_y x}}\right] - \operatorname{erf}\left[\frac{(y - Y/2)}{2\sqrt{a_y x}}\right]\right\} \left\{\operatorname{erf}\left[\frac{(z + Z/2)}{2\sqrt{a_z x}}\right] - \operatorname{erf}\left[\frac{(z - Z/2)}{2\sqrt{a_z x}}\right]\right\}$$

following equation:

Reference: An Analytical Model for Multidimensional Transport of a Decaying Contaminant Species, P.A. Domenico, 1987, Journal of Hydrology, 91, 49-58.

The three spreadsheets are:

QUICK_DOMENICO.XLS

This spreadsheet calculates the concentration anywhere in a plume of contamination at any time after a continuous, finite source becomes active.

FATBACK.XLS

This spreadsheet calculates the steady-state source concentration given the desired or target receptor concentration and location of the receptor. Given a source concentration calculated by Fatback, Quick_Domenico could be used to establish a site-specific standard for a property line compliance point.

SWLOAD.XLS

This spreadsheet uses a rearrangement of the Domenico equation to calculate concentrations at different points in the cross section of a plume at any distance from a continuous finite source at any time. The concentrations are

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then added and multiplied by the groundwater flux and can be used to estimate the mass loading of a particular contaminant from diffuse groundwater flow to a stream or surface water body.

These spreadsheets and documentation can be downloaded from the PA DEP web site at:

<http://www.dep.state.pa.us/dep/deputate/airwaste/wm/landrecy/MANUAL/Manual.htm#anchor86714>

QUICK_DOMENICO.XLS

~~This spreadsheet calculates the concentration anywhere in a plume of contamination at any time after the source became active. The model allows for three dimensional dispersion, first order decay, and retardation. The equation on which this spreadsheet is based is:~~

~~Reference: An Analytical Model for Multidimensional Transport of a Decaying Contaminant Species, P.A. Domenico, 1987, Journal of Hydrology, 91, 49-58~~

FATBACK.XLS

~~This spreadsheet calculates the source concentration given the desired receptor concentration and the location of the receptor. The equation used is the same as above except that the spreadsheet solves for C_0 , the source concentration at steady state conditions. Given the source concentration calculated by FATBACK.XLS, QUICK_DOMENICO.XLS could be used to establish a Site-specific Standard for a property line compliance point given the source concentration.~~

~~The various parameters used in these spreadsheets is given below:~~

~~X = distance from planar source to the location of concern (i.e., property line) along the center line of the plume. In the case of BAKDOM3D, X is the distance from the receptor to the source along the centerline of the plume.~~

~~$C(x,y,z,t)$ = the concentration of the contaminant at a distance X from the source, along centerline of plume in mg/L at time t (days)~~

~~C_0 = the highest concentration of the contaminant in the groundwater at the source in mg/L.~~

~~α_x = dispersivity in the x direction (ft) — often initially estimated as $.1 * X$.~~

~~α_y = dispersivity in the y direction (ft) — often initially estimated as $\alpha_x / 3$.~~

~~α_z = dispersivity in the z direction (ft) — often initially estimated as $\alpha_x / 20$~~

~~k = hydraulic conductivity (ft/day)~~

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i = hydraulic gradient

n = porosity (entered as a decimal fraction) — i.e., .25

v = seepage velocity (k_i/nR), where $R=1+(K_{oc})(f_{oc})(\rho_b)/n$

where K_{oc} = organic carbon partition coefficient

f_{oc} = fraction of organic carbon

ρ_b = dry bulk density of soil

λ = first order decay constant

S_w = width of source area (ft)

S_z = thickness of source area (ft)

x, y, z — these are the spatial coordinates in the horizontal, transverse and vertical directions that define the point you want to know the concentration of.

t — this is time in days since the plume source started moving

f) Calibration and Sensitivity

As stated in ASTM D 5447, calibration is the process of adjusting hydraulic parameters, boundary conditions and initial conditions within reasonable ranges to obtain a match between observed and simulated potentials, flow rates or other calibration targets. In working with sites under Act 2, an obvious calibration target is matching the model output to existing, and, if known, historical geometry and concentration of plume contaminants. The Act 2 final report should include a discussion of calibration targets, and an analysis and significance of residuals (differences between modeled and actual contaminant concentrations).

Sensitivity analysis is an evaluation of which model parameters have the most influence on model results. The parameters to which the model is most sensitive should be identified. Those parameters which have the most influence on model results are those which should be given the most attention in the data collection phase.

g) Predictive Simulations

Fate and Transport models may be used in the Land Recycling Program to make predictions of future contaminant concentrations. Uses may include:

- Predicting the maximum concentrations that will occur at downgradient compliance points (usually property boundaries) for the Statewide health Standard in the case of both used and non-use aquifers;

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- Predicting whether groundwater contamination above an MSC will extend beyond 1000 feet in the case of non-use aquifers, and if it will be at or below the MSC for groundwater in these areas within the next 30 years;
- In cases where the fate and transport analysis indicates that a standard may not be maintained at some time in the future, a post-remediation care plan will be needed.
- If post-remediation care is required, a “post audit” of the fate and transport model should be performed. In a post audit, the fate and transport model’s predictions are compared to continued monitoring data collected during the post remediation care period to check the validity and accuracy of previous model predictions. Monitoring wells for the post-audit must be located at points where they would be sensitive to auditing the model. This may not coincide with the property line compliance point if the plume would not be expected to migrate to the compliance point by the time of the post-audit.
- Post-audits should be performed on the model during the attainment monitoring phase (usually a minimum of two years) as a check on model predictions.

h) Fate and Transport Model Report

With the exception of those projects which do not require submission of a fate and transport model, the following general report format should be used to the extent applicable to adequately document the modeling effort.

The following format is modified after that in ASTM D 5447:

1.0 Introduction

1.1 General Setting

1.2 Study Objectives- which Act 2 standard is being demonstrated and what is the purpose of the modeling

2.0 Conceptual Model

2.1 Aquifer System Framework

2.2 Groundwater Flow Model

2.3 Hydrologic Boundaries

2.4 Hydraulic Boundaries

2.5 Sources and Sinks

3.0 Computer Code

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- 3.1 Code Selection-justification for use of analytical, numerical or other analysis
- 3.2 Code Description- name and version of analysis, model assumptions and limitations, name of organization or person which has developed the analysis

- 4.0 Groundwater Flow Model Construction
 - 4.1 Model Grid- state if fixed by model
 - 4.2 Hydraulic Parameters- state source such as field determined or literature. Cite relevant section of Site Characterization report or literature reference.
 - 4.3 Boundary Conditions- state if fixed by model
 - 4.4 Selection of Calibration Targets

- 5.0 Calibration
 - 5.1 Residual Analysis
 - 5.2 Sensitivity Analysis
 - 5.3 Model Verification, if applicable

- 6.0 Predictive Simulations- Indicate relation to applicable Act 2 standard

- 7.0 Summary and Conclusions
 - 7.1 Model Assumptions/Limitations
 - 7.2 Model Predictions
 - 7.3 Recommendations- including planned post-audit activities during post remediation care plan if required

- 8.0 Figures and Tables-
 - 8.1 model grid or axes oriented on the site map
 - 8.2 input and output files

3. Impacts to Surface Water from Diffuse Flow of Contaminated Groundwater

Sections 250.309 and 250.406 of the Act 2 regulations provide for determining compliance with surface water quality standards from a diffuse surface or groundwater discharge. For many cases, this will involve the diffuse flow of a groundwater plume into a stream.

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The following formula may be used to evaluate impacts on surface water from contaminated groundwater that will discharge into a stream. It assumes that the total contaminant mass load into the stream is constant and the diffuse flow into the cross-sectional area of the stream is uniformly mixed:

$$C_{sw} = \frac{Q_{gw} \times C_{gw}}{Q_{sw}}$$

where:

Q_{gw} = groundwater discharge from cross-sectional area of plume into stream (L³/T)

This may be estimated as kiA where :

k = hydraulic conductivity in (L/T)

i = hydraulic gradient at design flow conditions

A = cross-sectional area of plume at point of stream intersection (L²)

C_{gw} = area weighted average concentration of contamination in plume (mass/vol e.g., $\mu\text{g}/\text{L}$)

Q_{sw} = surface water quantity upstream of the site at design flow conditions (L³/T)

For carcinogens use Harmonic Mean Flow

For noncarcinogens use Q_{7-10}

Q_{7-10} = 7day/10year low flow

C_{sw} = surface water concentration (mass/vol)

C_{sw} is then compared to the applicable PADEP in stream water quality standard from Chapter 16 of Title 25.

Example:

Based on the site characterization and use of a fate and transport model a site located 400 feet from a stream has been projected to exhibit a plume of benzene with an area weighted average concentration at the stream boundary of 10 ug/l. The plume width and depth are estimated as 250 feet and 25 feet respectively. Hydraulic conductivity and hydraulic gradient based on the site characterization is 1×10^{-3} cm/sec and .048 respectively. The Harmonic Mean flow for the stream is 1 cfs and the in-stream water quality criterion for benzene is 1 $\mu\text{g}/\text{L}$.

$Q_{gw} = 1 \times 10^{-3} \text{ cm/sec} \times 1 \text{ ft}/30.48 \text{ cm} \times .048 \times (250\text{ft.} \times 25 \text{ ft.}) = .00984 \text{ ft}^3/\text{sec}$

$C_{gw} = 10 \mu\text{g}/\text{L}$

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$$Q_{sw} = 1 \text{ ft}^3/\text{sec}$$

$$C_{sw} = 0.098 \text{ } \mu\text{g/L}$$

Since the calculated in-stream concentration is below the water quality criterion of 1 $\mu\text{g/L}$, the surface water quality criterion has been met.

If the results of the mass balance analysis techniques and appropriate sampling for groundwater/surface water mixing at design flow conditions indicate that surface water quality standards are being achieved, no further action is required. If the results indicate that surface water quality standards are not being achieved, representative sampling of the surface water may be conducted to directly determine if the water quality standards are being achieved. If the results of the representative sampling of the surface water quality indicate that the surface water quality standards are being met, no further action is required. If the results of the modeling and further sampling, if any, indicate that surface water quality standards are not being met, the person shall take further action to attain the surface water quality standards, unless a waiver is obtained pursuant to Section 250.406(c).

B. Guidance for Attainment Demonstration with Statistical Methods

1. Introduction

The requirement to apply statistical methods to verify the cleanup of a site is emphasized in Act 2. Sections 302, 303 and 304 of Act 2 require that attainment of a standard be demonstrated by the collection and analysis of samples from affected media (such as surface water, soil, groundwater in aquifers at the point of compliance) through the application of statistical tests set forth in regulation. The Act also requires the Department to recognize those methods of attainment demonstration generally recognized as appropriate for that particular remediation.

Statistical methods are emphasized because there is a practical need to make decisions regarding whether a site meets a cleanup standard in spite of uncertainty. The uncertainty arises because we are able to sample and analyze only a small portion of the soil and groundwater at a site, yet we have to make a decision regarding the entire site.

The purpose of this section is to provide guidance for the use of statistics to demonstrate that a site has attained a cleanup standard under Act 2. It is intended to address certain key issues pertinent to the sampling and statistical analysis under Act 2, to provide references for proper statistical analysis and, if necessary, to provide examples of applying statistical procedures in detail. It is not intended to address every statistical issue.

For statistical attainment issues not addressed directly in this manual or the Act 2 regulations, a person may consult the latest EPA documents for additional guidance. USEPA guidance documents (USEPA 1989b, 1992b, 1992c, 1996) are particularly helpful. They provide detailed statistical procedures for demonstration of attainment and data analysis. Three of these documents are available from the USEPA World Wide Web Server at <http://www.epa.gov/ces/pubs.htm>. EPA QA/G-9 (USEPA 1996) is available from the World Wide Web at http://es.inel.gov/ncerqa/qa/qa_docs.html.

For groundwater characterization, persons should consult DEP "Groundwater Monitoring Guidance Manual, February 29, 1996" (Attachment V.H), which provides general information on groundwater monitoring and sampling issues, such as monitoring well construction, locations and depths of monitoring wells, and well abandonment procedures. The DEP Groundwater Monitoring Guidance Manual provides a good summary of various statistical methods used for groundwater characterization.

Other references cited in this document and standard texts may be used to perform the procedures to demonstrate attainment as appropriate. If necessary, professional services should be obtained.

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When we consider applying statistical methods to demonstrate the attainment of a risk-based cleanup standard, it is important to realize that three components may influence the over-all stringency of this cleanup standard:

- The first component is the magnitude, level, or concentration that is deemed protective of human health and the environment. The development of risk-based cleanup standards is addressed in the Act 2 regulations and Department's risk assessment guidances.
- The second component of the standard is the sampling that is done to evaluate whether a site is above or below the standard.
- The final component is how the resulting data are compared with the standard to decide whether the remedial action was successful (a statistical analysis).

Persons overseeing cleanup must look beyond the cleanup level and explore the sampling and statistical analysis that will allow evaluation of the site relative to the cleanup level. This guidance is intended to address statistical analysis and sampling components that may affect the stringency of cleanup standards.

2. Data Quality Objectives Process, Sampling, and Data Quality Assessment Process

An important issue regarding sampling and statistical analysis is the quality assurance (QA) management considerations associated with these activities. Steps for the QA management process, in general, can be divided into three phases: planning, implementation and assessment. During the planning phase, a sampling and analysis plan is developed based on Data Quality Objectives (DQO). The implementation phase includes sampling execution and sample analysis. The assessment phase includes Data Quality Assessment (DQA) (See Section 250.702(a) of the regulations).

To help a person design a scientific and resource-effective sampling program, EPA has provided guidance on developing Data Quality Objectives (USEPA 1993). The DQO process allows a person to define the data requirements and acceptable levels of decision errors, before any data are collected. The DQO process should be considered in developing the sampling and analysis plan, including the quality assurance plan.

As stated in the EPA guidance (USEPA 1993), the DQO process includes the following seven steps:

- State the problem.
- Identify the decision.
- Identify inputs to the decision.

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- Define the spatial and temporal boundaries of the decision.
- Develop a decision rule.
- Specify limits on decision errors.
- Optimize the design for obtaining data.

Step 4 of the DQO process, defining the spatial and temporal boundaries of the decision, is particularly important, because it prevents pooling and averaging data in a way that could mask potentially useful information. Activities in this step include:

- Define the domain or geographic area within which all decisions must apply. Some examples are property boundaries, operable units, and exposure areas.
- Specify the characteristics that define the population of interest. Identification of multiple areas of concern - each with its own set of samples and descriptive statistics - will help to reduce the total variability if the areas of concern are defined so that they are very different in their contaminant concentration profiles. For example, the top 2 feet of soil are defined as surface soil. Another example is to define contaminated soil that has been impacted by separate-phase liquid (SPL) as SPL-impacted soil.
- When appropriate, divide the population into strata that have relatively homogeneous characteristics. This helps to reduce the variability in each data set.
- Define the scale of decision making. The scale of decision making is the smallest area, volume, or time frame of the media in which decision errors are to be controlled. This is also the unit that will be assumed to generate a “statistical unit” of possible measurements which allows the assessment and control of decision errors. Examples are remediation units, exposure units, and hot spots.
- Determine the time frame to which the study data apply. It may not be possible to collect data over the full time period to which the decision will apply. Therefore a decision should be made regarding the most appropriate time frame that the data should reflect.
- Determine when to collect samples. Conditions at the site may vary due to seasons, weather or other factors. Therefore a decision should be made regarding the most appropriate time period to collect data that will reflect the conditions that are of interest.
- Identify any practical constraints on data collection, such as seasonal or meteorological conditions, unavailability of personnel, time, or equipment.

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At the completion of the DQO process, information obtained from the DQO process can be used to develop a sampling and analysis plan, including quality assurance/quality control plan.

Unless otherwise specified or approved by the Department, systematic sampling (grid sampling) designs should be used in developing the sampling and analysis plan for demonstrating attainment of soil cleanup standards (See Section 250.703(c) of the regulations). Systematic random sampling is a grid sampling design with a random starting point. Systematic random sampling provides better coverage of the soil study area than simple random sampling. Limitations and procedures to implement systematic sampling can be found in Sections 5.3 and 6.5 of EPA guidance (USEPA, 1989b). A square grid and a triangular grid are two common patterns used in systematic sampling. To avoid grid pattern corresponding to patterns of contamination, EPA (USEPA 1992c) recommended the use of unaligned grid sampling design (Gilbert, 1987, p.94). Unaligned grid sampling design maintains the advantage of uniform coverage while incorporating an element of randomness in the choice of sampling locations. To obtain unbiased estimate the variance of the mean, multiple systematic sampling approach (Gilbert, 1987, p.97) may be needed.

To generate a grid sampling design, a computer random number generator or a random number table may be used, such as Table IV -1.

After the environmental data have been collected and validated in accordance with the sampling and analysis plan (including the QA/QC plan), data must be assessed to determine whether the DQOs are met. This is the Data Quality Assessment (DQA) process. EPA has developed guidance on DQA (USEPA, 1996).

The DQA process involves the following five steps(USEPA, 1996):

- Review the DQOs and sampling design.
- Conduct a preliminary data review.
- Select the statistical test.
- Verify the underlying assumptions of the statistical test.
- Perform the statistical hypothesis test and draw conclusions that address the data user's objectives.

A properly implemented DQA process can help to determine if planning objectives were achieved. The following discussions will address key statistical issues that are pertinent to Act 2 and are encountered during these DQO and DQA processes.

3. Preliminary Data Review

Preliminary data review (also known as exploratory data analysis in the DEP Groundwater Monitoring Guidance Manual; PaDEP, 1996) includes the use of graphical techniques and calculation of summary statistics. Preliminary data review should be performed whenever data are used. By reviewing the data both numerically and graphically, one can learn the “structure” of the data and identify limitations for using the data. Graphical methods include histograms, probability plots, box charts, and time-series plots to visually review the data for trends or patterns. EPA and most statistical texts recommend that time-series data should be graphed. This visual approach allows for a quick assessment of the statistical features of the data. Calculations of summary statistics are typically done to characterize the data and make judgments on the central tendencies, symmetry, presence of outliers, etc. Preliminary data review is critical in selecting additional appropriate mathematical procedures.

Graphical and parametric statistical procedures discussed here are included in many introductory statistics textbooks (*e.g.*, Iman and Conover, 1983 and Ott, 1988) and are available in many computer statistics packages, such as SAS and DataQUEST (EPA QA/G-9D). SAS is available to DEP employees through DER001 network. EPA is developing DataQUEST (EPA QA/G-9D) to support Data Quality Assessment (DQA) process. DataQUEST (EPA QA/G-9D) will be available from World Wide Web at http://es.inel.gov/ncerqa/qa/qa_docs.html or <http://www.epa.gov/r10earth/offices/oea/qaindex.htm>.

i) Summary Statistics

Basic summary statistics can be used to characterize groundwater monitoring data. Summary statistics include median, interquartile range (IQR), mean, standard deviation, and range. Median and IQR are determined from percentiles. Median is the 50th percentile and IQR is the 25th to 75th percentile. Median indicates the “center” of data values. The mean is another measure of center but only if data are normally or symmetrically distributed. Mean and standard deviation are required values with parametric procedures. Range is the minimum to maximum values. Procedures for such summary statistics are found in introductory statistics texts.

ii) Graphical Procedures

Refer to Cleveland (1993) or EPA QA/G-9 (USEPA, 1996) for a general reference on graphical procedures. The use of boxplots is also described in the EPA Addendum (USEPA, 1992a).

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Histogram - A histogram is a graphic display of frequency distribution. The area within the bar represents the relative density of the data.

Boxplots - A boxplot summarizes a data set by presenting the percentile distribution of the data. The “box” portion indicates the median and interquartile range (IQR). IQR is the middle 50 percent of data. Difference in the size of box halves represents data skewness.

Normal and symmetrical distributions will have equal size box halves. Extreme outliers are displayed as individual points that are recognized easily. Boxplots can be constructed by hand; however, many computer statistical packages will do them.

The boxplot of a lognormal distribution will have noticeably different-sized box halves. Lack of IQR overlap for different data sets will indicate a probable significant difference. Boxplots of seasonally grouped data can be used to detect data seasonality.

Time Series Plots - A time series plot displays individual data points on a time scale. A monthly scale can help to identify seasonal variation. A yearly scale also can identify possible trends. Superimposing data from multiple sampling locations may provide additional information. Improved trend information is often available with data smoothing. One smoothing procedure showing movement of the “center” of data over time is LOWESS. This procedure is most helpful with data having substantial variability and a long period of record. LOWESS requires computer software.

Control Charts - Control charts are used to define limits for an analyte that has been monitored at an uncontaminated well over time. This procedure is a graphical alternative to prediction limits.

A common technique is the Shewhart-CUSUM control chart that plots the data on a time scale. Obvious features such as trends or sudden changes in concentration levels could then be observed. With this method, if any compliance well has a value or a sequence of values that lie outside the control limits for that analyte, it may indicate statistically significant evidence of contamination.

The control chart approach is recommended only for uncontaminated wells, a normal or lognormal data distribution with few nondetects, and for a dataset that has at least eight independent samples over a one year period. This baseline is then used to judge the future samples. See the EPA Interim Final Guidance (USEPA, 1989a, Section 7) and the EPA Addendum (USEPA, 1992a, Section 6.1) for procedures.

4. Statistical Inference and Hypothesis Statements

Statistical procedure that is designed to allow the extrapolation from the results of a few samples to a statement regarding the entire site is known as statistical inference. Statistical inference allows decision making under uncertainty and valid extrapolation of information that can be defended and used with confidence to determine whether the site meets the cleanup standard.

The goal of statistical inference, the process of extrapolating results from a sample to a larger population, is to decide which of two complementary hypotheses, null hypothesis and alternative hypothesis, is likely to be true.

In general, statistical inference procedures include the following steps:

- (1) A null hypothesis and its alternative hypothesis are drawn up. The null hypothesis is developed in such a way that the probability of Type I error can be determined. The Type I error is an error that we falsely reject the null hypothesis, when the null hypothesis is true. Type I error is also known as false positive error.
- (2) Decide the level of significance, α . This controls the risk of committing a Type I error.
- (3) Establish a decision rule for each scale of decision making that is derived from step 4 of the DQO process.
- (4) Determine the sample size, n . This is the number of environmental samples needed to make decision. Obtain data through the implementation of sampling and analysis plan.
- (5) Apply the decision rule to the data. The null hypothesis is rejected or not rejected. Rejection of the null hypothesis implies acceptance of the alternative hypothesis.

Section 250.707(d)(1) of the regulations has specified the ground rules of hypothesis statements under Act 2. For demonstration of attainment of Statewide health or site-specific standards, the null hypothesis (H_0) is that the true site arithmetic average concentration is at or above the cleanup standard, and the alternative hypothesis (H_a) is that the true site arithmetic average concentration is below the cleanup standard. When statistical methods are to be used to determine that the background standard is exceeded, the null hypothesis (H_0) is that the background standard is achieved and the alternative hypothesis (H_a) is that the background standard is not achieved.

To understand the rationale of hypothesis testing, let us consider a nonstatistical hypothesis testing example - the process in which an accused individual is judged to be innocent or guilty in a criminal court. Under our legal system, we feel that it is a more grievous mistake to convict an innocent

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man than to let a guilty man go free. Therefore, the accused person is presumed to be innocent under our legal system. The burden of proof of his guilt rests upon the prosecution. The prosecutor must present sufficient evidence to the jury in order to convict the defendant while the defendant's lawyer would want to throw any reasonable doubt into the evidence presented by the prosecutor in order to get acquittal verdict for the defendant. Using the language of hypothesis testing, we want to test a null hypothesis (H_0) that the accused man is innocent. That means that an alternative hypothesis (H_a) exists, that the defendant is guilty. The jury will examine the evidence and decide whether the prosecution has demonstrated sufficiently that the evidence is inconsistent with the null hypothesis (H_0) of innocent. If the jurors decide that the evidence is inconsistent with H_0 , they reject that hypothesis and therefore accept the alternative hypothesis (H_a) that the defendant is guilty.

Similar to the above legal process example, because we feel that it is a more serious mistake to declare a dirty site to be clean than to declare a clean site to be dirty under the Statewide health and site-specific standards, we choose the following null hypothesis statement: the true site arithmetic average concentration is at or above the cleanup standard. The null hypothesis is assumed to be true unless substantial evidence shows that it is false. The demonstration of attainment must be presented with sufficient evidence in order to show that the post-remediation condition at the site is not consistent with the null hypothesis. We use "true site arithmetic average concentration" here because arithmetic average concentration is representative of the concentration that would be contacted at a site over time and toxicity criteria that are used to develop cleanup standards are based on long-term average exposure. The arithmetic average is appropriate regardless of the type of statistical distribution that might best describe the sampling data. We do not use geometric average concentration because the geometric mean of a set of sampling data bears no logical connection to the cumulative intake that would result from long-term contact with site contaminants.

It should be noted that the above hypothesis statements referring to the arithmetic average concentration does not force everyone to use 95% upper confidence limit (UCL) to infer the true site arithmetic average concentration. Methods other than the 95%UCL, such as tests for percentiles or proportions, also may be used provided that a person can document that high coverage of the true population mean occurs, (*i.e.*, the value used in a method equals or exceeds the true site arithmetic average concentration with high probability).

For the background standard, the null hypothesis (H_0) is that the background standard is achieved and the alternative hypothesis (H_a) is that the background standard is not achieved. The background standard is not risk-based. These hypothesis statements will allow some site concentrations to be

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higher than some background reference-area measurements without rejecting the null hypothesis. These hypothesis statements are consistent with USEPA guidance documents (USEPA, 1992c). If we reverse the hypothesis statements and presume that the background standard is not achieved, we would require most site concentrations to be less than the reference measurements in order to declare a site to be clean. In considering the cost of remediation, both the Department and USEPA believe that this requirement is unreasonable.

5. Selection of Statistical Methods

a) Factors Affecting the Selection of Statistical Methods

The selection of statistical methods for use in assessing the attainment of cleanup standards depends on the characteristics of the environmental media. In soils, concentrations of contaminants change relatively slowly, with little variation from season to season. In groundwater, the number of measurements available for spatial characterization is limited and seasonal patterns may exist in the data. As a result of these differences, separate procedures are recommended for the differing problems associated with soils and groundwater.

The selection of statistical methods also depends on remediation standards. There are three types of remediation standards under Act 2: background standards, Statewide health standards, and site-specific standards. Background standards are developed using background data. Statewide health standards and many site-specific standards are risk-based standards that are concentration limits based on risk assessment methodologies. At some sites, a site-specific standard could be a technology-based standard, such as capping a site to eliminate pathways. The cap must be designed to meet certain engineering specifications prescribed in numerical levels. A background standard is not a single number but rather a range of numbers. A statistical method used to demonstrate the attainment of the background standard is used to compare the distribution of data for a background reference area to the distribution of data for the impacted area. Different statistical methods are used to demonstrate the attainment of a risk-based concentration limit (a bright line standard).

As a result of the above factors, recommended statistical approaches are addressed separately based on environment media and remediation standards. The flowchart in Figure IV -1 provides a summary of recommended statistical methods described in Act 2 regulations. Since Act 2 also requires the Department to recognize those methods of attainment demonstration generally recognized as appropriate for a particular remediation, the Department will

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also accept other appropriate statistical methods that meet the performance standards described in 250.707(d)(2) of [the](#) Act 2 regulations.

Statistical methods generally can be classified into two categories: parametric procedures, and nonparametric procedures. The selection of a parametric or a nonparametric procedure depends on the distribution of the data, the percentage of nondetects, and the database size. However, both procedures have assumptions that must be met to be considered valid analyses.

Parametric Procedure - Assumptions of parametric procedures include a specific data distribution such as normal (also known as Gaussian or the bell-shaped curve) or lognormal (normality achieved by log-transforming the data), and data variances that are similar. In addition, the data are assumed to be independent.

Nonparametric Procedure - Assumptions for nonparametric tests also are important. Nonparametric procedures assume equal variances and that the type (shape) of distribution of the population is the same. In other words, nonparametric methods do not require a specific type of data distribution, which is different from assuming a normal distribution when using parametric statistics.

Nonparametric procedures may be preferred because they:

- are free from normal distribution assumptions thereby eliminating the need for normality tests and data transformations;
- are resistant to effects of outliers; and
- are usable when censored (*i.e.*, less-than detection values) data are present.

b) Recommended Statistical Procedures

In consideration of the factors described above, Section 250.707 of the Act 2 regulations provides recommended statistical procedures that can be used to demonstrate attainment of cleanup standards. The following discussions provide background information of these recommended methods.

i) Soil Risk-Based Standards

For risk-based standards, the selection of statistical parameters, such as mean, median or an upper percentile, to use in the statistical assessment decision depends on the toxicity criteria. Mean and median are useful for cleanup standards based on carcinogenic or chronic health effects and long-term average exposure. Upper proportion or percentile should be used if the health effects of the contaminant are acute or worst-case effects. Because the Statewide health standards are based on the evaluation of carcinogenic or chronic health effects and long-term average exposure, Cleanup Standard

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Scientific Advisory Board (CSSAB) has recommended that mean or median should be the statistical parameter of choice. Act 2 regulations allow the remediator to use the 75%/10X rule or the 95% upper confidence limit (UCL) of arithmetic mean to demonstrate attainment of Statewide health standard in soils. For UST release sites that have only localized (soil) contamination as defined in the storage tank program's Closure Guidance, and where the confirmatory samples taken in accordance with this technical guidance document result in fewer samples being taken than otherwise required, all sample results must meet the Statewide health standard. For the site-specific standard, the regulations recommend the use of the 95% upper confidence limit (UCL) of the arithmetic mean to demonstrate attainment in soils. Sections 250.707(b) and (c) of the regulations discuss statistical test appropriate to demonstrating compliance of surface soils with the Statewide health and site-specific standards.

(a) 75%/10X Rule

The 75%/10X rule is a statistical *ad hoc* rule that tests whether the true site median concentration is below the cleanup standard. This rule requires that 75% of the samples collected for demonstration attainment be equal to or below the risk-based cleanup standard and that no single sample result exceeds the risk-based standard by more than ten times (See Section 250.707(b)(1)(i) of the regulations).

For the 75%/10X rule, the number of sample points required for each distinct area of contamination is specified in Section 250.703(d) of the Act 2 regulations and is as follows:

- For soil volumes equal to or less than 125 cubic yards, at least eight (8) samples.
- For soil volumes up to 3,000 cubic yards, at least twelve (12) sample points.
- For each additional volume of up to 3,000 cubic yards, an additional twelve (12) sample points.
- Additional sampling points may be required based on site-specific conditions.

This recommendation of 8 to 12 samples at minimum is based on a simulation study using lognormal distributions (CSSAB 1996; Ruscitti, 1996). Because the heterogeneity of a volume of soil increases as the volume increases, the number of samples required to accurately demonstrate attainment would also increase.

It should be noted that the 75%/10X rule should not be used to demonstrate attainment of site-specific standard. The site-specific standard is based on site-specific risk assessment methodology, including the assumption that a

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receptor's long-term exposure is related to the true site arithmetic average concentration of a contaminant. Therefore, the 75%/10X rule is not appropriate for the site-specific standard.

(b) The 95% Upper Confidence Limit (UCL) of Arithmetic Mean

Using 95%UCL of the arithmetic mean as described in Section 250.707(b)(1)(ii) and 250.707(c) of the regulations is well documented in various EPA risk assessment or statistical guidances (USEPA, 1989b, 1989c, 1992c, 1996). The following formula can be used for calculating sample size (number of discrete soil samples) needed to estimate the mean :

$$n_d = \sigma^2 \{ (Z_{1-\beta} + Z_{1-\alpha}) / (C_s - \mu_1) \}^2$$

where α is the false positive rate; β is the false negative rate; $Z_{1-\alpha}$ and $Z_{1-\beta}$ are the critical values for the normal distribution with probabilities of $1-\alpha$ and $1-\beta$; C_s is the cleanup standard; μ_1 is the value of population mean under the alternative hypothesis for which the specific false negative rate (β) is to be controlled; σ is an estimate of true standard deviation of the population.

Please note that the above equation may generate exceedingly large sample size numbers (e.g., $>>50$). When some adjustments of the sample size are necessary based on practical and cost considerations, a person may use the equation to generate a smaller sample size by increasing the false negative rate or the detection difference $C_s - \mu_1$. Professional judgment should be used in calculating sample size versus the reliability of the statistical test. The false positive rate must not be greater than 0.20 for a nonresidential site and 0.05 for a residential site (Section 250.707(d)(2)(vii) of the regulations).

Procedures to calculate 95%UCL of arithmetic mean are provided in Attachments 1 and 2.

The following decision rule is used to determine if a site meets the cleanup standard:

- If 95%UCL of arithmetic mean is greater than or equal to C_s , conclude that the area is dirty.
- If 95%UCL of arithmetic mean is less than C_s , conclude that the area is clean.

Note that this rule uses the 95%UCL of the arithmetic mean to estimate the limit of the population mean. The decision rule is consistent with the hypothesis statements.

The primary assumptions of this method are independence of the data, and sample mean is approximately normally distributed or data are lognormally

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distributed. Examples of normal and lognormal distributions are shown in Figure IV-2. When the population is normally distributed, the sample mean is normally distributed, no matter the sample size. However, if the population distribution is unknown, Central Limit Theorem states that the distribution of sample means of random samples with fixed sample size (n) from a population with an unknown distribution will be approximately normally distributed provided the sample size (n) is large. This means that moderate violation of the assumption of normality for the population is acceptable when sample size is large.

For sample sizes up to 50, EPA recommends to use Shapiro Wilk W test for testing normality (USEPA, 1996). Other tests for normality, such as chi-square test and other goodness-of-fit test were discussed in Section 4.2 of EPA QA-G9 (USEPA, 1996). To test the independence of data, ordinary-runs test (Gibbons, 1990) can be used.

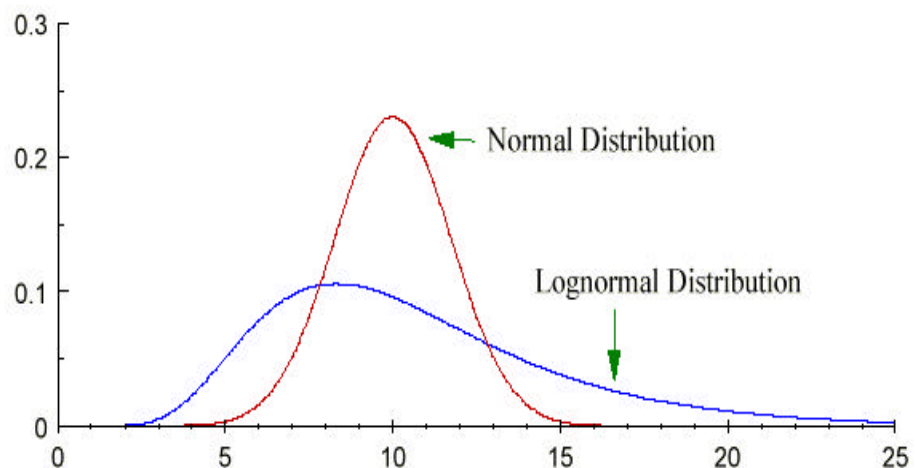


Figure IV -2. Examples of Normal Distribution and Lognormal Distribution

An important consideration regarding the 95%UCL of arithmetic mean is the use of composite sampling approach. Unless composite sampling is considered inappropriate (such as for volatile organic compounds), data from composite sampling can be more cost-efficient to estimate population mean and population variance than from discrete sampling (Edland et al., 1994; Patil et al., 1994). Composite sampling can reduce the laboratory analysis cost. Composite sampling may be considered, if appropriate, to obtain the 95%UCL of arithmetic mean. Equations to calculate the 95%UCL of arithmetic mean for composite sampling are available (Edland et al., 1994; Patil et al., 1994).

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(c) No Exceedance Rule

For cleanup of ~~localized contamination under the Underground Storage Tank Program~~ releases of petroleum products where full site characterization has not been conducted and remediation is guided by visual observation and/or field screening, ~~the~~ no exceedance rule ~~can~~ must be used as described in Section 250.707(b)(1)(iii) of the regulations as follows: ~~This rule requires that the maximum concentration at areas of concern does not exceed the cleanup standard. The number of samples required is specified~~

For sites where there is localized contamination as defined in the document entitled the document- "Closure Requirements for Underground storage Tank Systems" (DEP technical guidance document No. 2530-BK-DEP2008), samples shall be taken in accordance with that document.

For sites with contamination that does not qualify as localized under that document, samples shall be taken from the bottom and sidewalls of the excavation in a biased fashion that concentrates on areas where any remaining contamination above the Statewide health standard would most likely be found. The samples shall be taken from these suspect areas based on visual observation and the use of field instruments. If a sufficient number of samples has been collected from all suspect locations and the minimum number of samples has not been collected, or if there are no suspect areas, the locations to meet the minimum number of samples shall be based on a random procedure. The number of sample points required shall be determined in the following way:

- For 250 cubic yards or less of excavated contaminated soil, five samples shall be collected.
- For each additional 100 cubic years of excavated contaminated soil, one sample shall be collected.
- For excavation involving more than 1,000 cubic yards of contaminated soil, the Department will approve the confirmatory sampling plan.
- Where water is encountered in the excavation and no obvious contamination is observed or indicated, soil samples collected just above the soil/water interface shall meet the MSC determined by using the saturated soil component of the soil-to-groundwater numeric value.
- Where water is encountered in the excavation and no obvious contamination is observed or indicated, a minimum of two samples shall be collected from the water surface in the excavation.

All sample results shall meet the Statewide health standard.

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For sites where there is a release to surface soils resulting in excavation of 50 cubic yards or less of contaminated soil, samples shall be collected as described above, except that two samples shall be collected.

ii) Groundwater Risk-Based Standards

Statistical tests appropriate demonstrating compliance with groundwater standards are presented in Section 250.707(b)(2) of the regulations. Groundwater cleanup activities generally include site investigation, groundwater remediation, a post-treatment period allowing the groundwater to stabilize, sampling and analysis to assess attainment, and possible post-cleanup monitoring. Different statistical procedures are applicable at different stages in this cleanup process. The statistical procedures used must account for the changes in the groundwater system over time due to natural or man-induced causes. The specific statistical procedures used depend on the goals and quality of the monitoring data. The methods selected should be consistent with the goals of the monitoring. For example, a person may want to use regression analysis to decide when to stop treatment of groundwater. Regression analysis can be used to detect trends in contaminant concentration levels over time, to determine variables that influence concentration levels, and to predict chemical concentrations at future points in time. After terminating groundwater treatment, a person may want to use time trend analysis or plots of data to find if the groundwater has stabilized. After the groundwater has reached a steady state, the person may compare monitoring well concentrations to background reference well concentrations to determine whether the post-cleanup contamination concentrations are acceptable compared to the cleanup standards and may perform trend analysis or use plots of data to determine whether the post-cleanup contamination concentrations are likely to remain acceptable.

Once the groundwater has stabilized, it is recommended to use the 95% upper confidence limit of mean (USEPA, 1992b) or the following CSSAB ad hoc rules to compare with groundwater risk-based standards: In monitoring wells beyond the property boundary, the attainment criteria would be 75% of the sampling results from any given well being below the standard with no individual value being more than 2 times the standard (CSSAB 75%/2X rule). This rule would have to be met in each individual monitoring well.

To use the CSSAB ad hoc rules, 8 samples from each compliance well must be obtained during 8 consecutive quarters. Shorter sampling period requires the use of the no exceedance rule (Section 250.704(d)(3) of the Act 2 regulations).

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iii) Soil Background Standards

The determination of attainment of soil background standards will be based on a comparison of the distributions of the background concentrations of a regulated substance with the concentrations in an impacted area. Section 250.707(a)(1) of the regulations allows a person to use highest measurement comparison, combination of Wilcoxon Rank Sum test and Quantile test, or other appropriate methods to demonstrate attainment of background standards. No matter which method is used, Act 2 regulations require that the minimum number of samples to be collected is ten from the background reference area and ten from each cleanup unit. This requirement of ten samples is to ensure that any selected statistical test has sufficient power to detect contamination. The regulations do not specify the false negative rate because it is more appropriate to determine the false negative rate on a site-specific basis. For the background standard, the false negative rate is the probability of mistakenly concluding that the site is clean when it is contaminated. It is the probability of making a Type II error.

Background soil sampling locations must be representative of background conditions for the site, including soil type and depth below ground surface. Randomization of sampling at background reference and on-site locations must be comparable. EPA (USEPA, 1992c) recommends that samples be collected from background reference areas and cleanup units based on a random-start equilateral triangular grid. When a triangular grid may miss the pattern of contamination, EPA recommended to use an unaligned grid (Gilbert, 1987, p.94) to determine the sampling locations.

(a) Wilcoxon Rank Sum Test

This procedure (also known as Mann-Whitney U test) is a nonparametric test for differences between two independent groups. See Chapter 6 of the EPA Attainment, Volume 3 (USEPA, 1992c), and Section 250.707(a)(1)(ii) of the regulations.

For the Wilcoxon Rank Sum (WRS) test, the EPA states that Noether's formula may be used for computing the approximate total number of samples to collect from the background reference area and in the cleanup unit (USEPA 1992c).

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{12c(1-c)(Pr-0.5)^2(1-R)} \quad (\text{Noether's formula})$$

= total number of required samples.

where

α = specified Type I error rate

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β = specified Type II error rate

$Z_{1-\alpha}$ = the value that cuts off (100 α)% of the upper tail of the standard normal distribution

$Z_{1-\beta}$ = the value that cuts off (100 β)% of the upper tail of the standard normal distribution

c = specified proportion of the total number of required samples, N , that will be collected in the reference area

m = number of samples required in the reference area = $c \times N$

Pr = specified probability greater than 1/2 and less than 1.0 that a measurement of a sample collected at a random location in the cleanup unit is greater than a measurement of a sample collected at a random location in the reference area. This value is specified by the user. See Section 6.2.2 of USEPA, 1992c for methods to determine Pr .)

R = expected rate of missing or unusable data

n = number of samples required in the cleanup unit = $N - m$

The underlying assumptions for Wilcoxon Rank Sum test are random sampling, independence assumption of selecting sampling points, and that the distributions of the two populations are identical in shape and dispersion. The distributions need not to be symmetric. When applied with the Quantile test, the combined tests are most powerful for detecting true differences between two population distributions. When using the combined test, caution should be exercised to ensure that the underlying assumption of equal variance is met. An appropriate test for dispersion, such as Levene's test can be used. Unequal dispersion of data due to higher concentration of contaminant at the site should be properly addressed.

Procedures and an example of using the Wilcoxon Rank Sum test are in Attachment 3.

(b) Quantile Test

The Quantile test (Johnson et al. 1987), described in Section 250.707(a)(1)(ii) of the regulations, is performed by first listing the combined reference-area and cleanup-unit measurements from smallest to largest as was done for the Wilcoxon Rank Sum (WRS) test. Then, among the largest r measurements (*i.e.*, r is the number of measurements) of the combined data sets, a count is made of the number of measurements, k , that are from the cleanup unit. If k is sufficiently large, then we conclude that the cleanup unit has not attained the reference-area cleanup standard. The Quantile test is more powerful than the WRS test for detecting when only one or a few small portions of the cleanup

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unit have concentrations larger than those in the reference area. Also, the Quantile test can be used when a large proportion of the data is below the limit of detection. See Chapter 7 of the EPA attainment guidance (USEPA, 1992c).

For Quantile test, EPA recommends to use look-up tables to determine the number of measurements that are needed from the background reference area and the cleanup unit (Section 7.2 of USEPA, 1992c).

Procedures and an example of using the Quantile test are in Attachment 4. The null hypothesis (H_0) and alternative hypothesis (H_a) statements for the Quantile test are:

$H_0: \varepsilon = 0, \Delta/\sigma = 0$

$H_a: \varepsilon > 0, \Delta/\sigma > 0$

where

ε = the proportion of the soil in the cleanup unit that has not been remediated to background reference levels

Δ/σ = amount (in units of standard deviation, σ) that the distribution of 100% of the measurements in the remediated cleanup unit is shifted to the right (to higher measurements) of the distribution in the background reference area

The underlying assumptions for Quantile test are random sampling, independence assumption of selecting sampling points, and that the distributions of the two populations have the same dispersion (variance). See Chapter 4 of EPA QA/G-9 (USEPA, 1996) for methods and examples to verify underlying assumptions.

iv) Groundwater Background Standards

There are two general categories of background conditions. The first is naturally occurring background or area wide contamination, neither of which is expected to exhibit seasonal patterns or trends. The second is background associated with a release of regulated substances at a location upgradient from the site that may be subject to such patterns and trends.

For naturally occurring background or area wide contamination, It is recommended that a minimum of twelve samples be collected from any combination of upgradient monitoring wells, provided that all data collected are used in determination of background concentrations. This same number of samples must then be collected from monitoring wells impacted by a release on the site during the same sampling event. In both cases, this sampling may be accelerated such that all samples be collected as quickly as possible so long as the frequency does not result in serial correlation in the data. The resulting

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values may be compared using nonparametric or parametric methods to compare the two populations, such as using the combination of Wilcoxon Rank Sum test and Quantile test described previously. When comparing with the background results, the sampling results in the plume on site should not exceed the sum of the arithmetic average and three times standard deviation calculated for the background reference area [Section 250.708(a)(3)(vii)].

For background associated with a release of regulated substances at a location upgradient from a property, the background groundwater concentrations will be determined at the hydrogeological upgradient property line of the property, or a point hydrogeologically upgradient from the upgradient property line that is unaffected by the release.

Attainment of the background standard must be demonstrated wherever the contamination occurs. There may be some mass of a particular contaminant added to groundwater on the property. However, that additional mass cannot result in concentrations which exceed the concentration measured at the property line, nor can it be used to allow releases on the property. Background concentrations are not related to a release at the site (Section 103 of Act 2).

In the event contamination migrates off the property, concentrations at the downgradient property boundary must be equal to or less than the background concentrations measured where groundwater enters the property. If there has been a release on-property, the plume migrating beyond the property boundary must also be remediated.

For background associated with an upgradient release of regulated substances, Section 250.707(a)(2) of Act 2 regulations allow the use nonparametric tolerance limit procedure. Nonparametric tolerance limit procedure requires at least 8 samples from each well over 8 quarters to have sufficient power to detect contamination. Once the nonparametric upper tolerance limit is established for upgradient data, data from downgradient compliance wells can be compared to the limit. A resampling strategy can be used when an analyte exceeds the nonparametric upper tolerance limit. The well is retested for the analyte of concern and the value is compared to the nonparametric upper prediction limit. These two-phase testing strategies can be very effective tools for controlling the facility-wide false positive rate while maintaining a high power of detecting contamination. See Sections 5.2.2 and 5.2.3 of the EPA Addendum (USEPA, 1992a) which describes the procedures to use along with recommended coverage and confidence levels.

6. Additional Information on Statistical Procedures

This section provides an overview regarding various other statistical methods available to use to determine if a cleanup activity is successful. The EPA

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Interim Final Guidance (USEPA, 1989a), EPA Addendum (USEPA, 1992a), EPA Soil Attainment (USEPA, 1989b), EPA Groundwater Attainment (USEPA, 1992b), EPA Soil Reference-Based Standards Attainment (USEPA, 1992c) and EPA QA/G-9 (USEPA, 1996) describe and provide examples for both the parametric and nonparametric methods. See additional discussions in Helsel and Hirsch (1992), Conover (1980), Gilbert (1987), and Davis and McNichols (1994, Parts I and II).

i) Interval Tests

Statistical Intervals - Statistical interval tests can be used independently for comparing with a numerical value or in combination with other tests for comparing populations. Statistical intervals include three main types: tolerance intervals, prediction intervals, and confidence intervals. Which ones are used depend on the goals of the data analysis (see USEPA (1992a) Section 4 or Chapters 6 and 7 of USEPA (1989b) for procedures).

Tolerance Intervals - Tolerance intervals will typically be the most useful interval test. They are used to determine the extent of data that is within a standard (like an MCL) or ambient level. Parametric tolerance intervals can be computed by assuming a lognormal distribution.

Prediction Intervals - Prediction intervals are used to determine if the next one or more samples are within the existing data distribution at a certain confidence level. The prediction interval contains $100 * (1 - \alpha)$ percent of the distribution. A smaller α value will include a larger range of data. Prediction intervals are used for intrawell (single well) comparisons, and with comparison of a compliance well with a background well.

Confidence Intervals - Confidence intervals contain a specified parameter of the distribution (such as the mean of the data) at a specified confidence level. Confidence intervals do not address extreme values. The step-by-step procedures to calculate the upper confidence of mean are provided as attachments to this statistical guidance.

ii) Tests for Comparing Populations

The following tests are outlined in the EPA Interim Final Guidance (USEPA, 1989a) and the EPA Addendum (USEPA, 1992a). These are some of the EPA's recommended tests for analysis of groundwater data between upgradient and downgradient well groups, downgradient wells and a health-based standard, or of intrawell (single well) comparisons. This does not include all potentially satisfactory statistical tests.

Analysis of Variance (ANOVA) - ANOVA includes a group of procedures used for comparing the means of multiple (3 or more) independent groups

such as upgradient wells and downgradient wells. The ANOVA methods are used to determine if there is statistically significant evidence of contamination at downgradient wells compared to an upgradient well, or groups of wells.

The one-way ANOVA method is described with examples in Section 5.2 of the EPA Interim Final Guidance (USEPA, 1989a). This is the EPA recommended procedure for comparing data that do not violate the assumptions of normal distribution and approximately equal variances.

However, as the number of wells (or groups) increases at a site, the power of ANOVA to detect individual instances of contamination decreases. For this reason, tolerance and prediction intervals with retesting provisions are often much better procedures to use.

Kruskal-Wallis Test - If assumptions of the one-way ANOVA test are "grossly" violated, the nonparametric Kruskal-Wallis test is used for more than 2 independent groups of data. It can be used for comparison of upgradient water quality to water quality from many downgradient wells in one procedure. Alternatively, if the wells are grouped by some characteristic (*e.g.*, depth, geology, location, season), comparisons among other groups can be made.

If the null hypothesis (no change) is rejected by Kruskal-Wallis (*i.e.*, the test statistic exceeds the tabulated critical value), then pairwise comparisons should be made to determine what wells are contaminated (see Gilbert (1987), Section 18.2.2; the EPA Addendum (1992a), Section 3.1; and the EPA Interim Final Guidance (1989a), Section 5.2.2). The underlying assumptions are the distributions of the independent populations are identical in shape (variance), but the distributions need not to be symmetric.

t-test - The t-test is a parametric, ANOVA type of test used to assess differences in means of two independent groups. This test assumes normal distributions and equal variances for both groups. The t-test is best limited to situations where the data sets are too small to use nonparametric procedures. For example, if background water quality is limited to two or three samples, the t-test can be used to test for differences between background and compliance data.

iii) Trend Tests

Considerations - When monitoring data have been collected over several years or more, trend tests allow the determination of the change in distribution of data over time. In addition to water quality trends, a time series of monitoring data may contain characteristics of seasonality and serial correlation. Other complicating factors include changes in laboratories or procedures involving the sampling and analysis of the analyte.

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Seasonality and serial correlation interfere with trend tests either by reducing the power to detect trends or giving erroneous probabilities. Correction for seasonality is available for tests presented here. Serial correlation exists if a data point value is at least partially dependent on nearby data point values. For a given data set, serial correlation decreases with increasing temporal distance between samples. Harris and others (1987) reported difficulty detecting serial correlation in 10 years or less of quarterly groundwater data. Therefore, correction is not recommended for quarterly data. Serial correlation correction is available for Seasonal Kendall trend test (Hirsch and Slack, 1984), but has reduced power with small data sets and not recommended for a monthly time series that is less than 5 years.

Parametric Trend Tests - Parametric trend tests are based on regression methods and allow compensation for exogenous effects (outside influences). Regression analysis between two variables can be used to calculate the correlation coefficient (r). The closer r is to one, the closer the relationship is between the two variables. A t-test of correlation can be done on r to see if it is significant (see Davis, 1987, Chapter 2 ; USEPA, 1992a, Chapter 6; USEPA, 1996, Section 4.3.2).

Mixed (*i.e.*, parametric and nonparametric methods) methods also are available when removing the effects of exogenous variables. Helsel and Hirsch (1992) present a thorough review of trend analysis. Methods for detecting trends also are presented in (Chapter 16 of Gilbert 1987).

Because regression techniques are based on the assumption of a normal distribution of the data, a nonparametric approach may have to be used.

Nonparametric Trend Tests - The Mann-Kendall trend test is a nonparametric test for monotonic (steadily upward or downward) trend. (Gilbert, 1987; Section 4.3.4 of USEPA, 1996).

This test requires constant variance in data. Nonconstant variance may be changed to constant variance with a power transformation. Logarithm transformation is usually most appropriate. This transformation does not affect the test statistic. Decision rules, exact test tables, normal approximation formulas, and correction for ties can be found in Helsel and Hirsch (1992); Gilbert (1987) and many introductory statistics texts. When a trend is present, the slope of fitted line can be estimated using Sen's estimator (see Gilbert, 1987; Section 4.3.3 of USEPA, 1996).

The Seasonal Kendall trend test is a seasonally corrected Mann-Kendall trend test. This should be applied when time series graphs or boxplots of data indicate the presence of seasonal variation. See Chapter 17 of Gilbert (1987).

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7. Calculation of UCL of Mean When the Distribution of the Sampling Mean is Normal

The following is a step-by-step description of the approach used to calculate confidence limits of arithmetic mean when the distribution of the sampling mean is normal. For data sets of lognormal distribution, the approach in Section 8 should be used instead.

1. Calculate the sample mean by dividing the sum of the total readings by the total number of readings:

$$\bar{X} = (X_1 + X_2 + \dots + X_n) / n$$

2. Calculate the sample variance (S_b^2) by taking the sum of the squares of each reading minus the mean and dividing by the degrees of freedom (df, the total number of samples minus one):

$$S_b^2 = [(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2] / (n-1)$$

3. Calculate the standard deviation (S_b) by taking the square root of the variance (S_b^2):

$$S_b = \sqrt{(S_b^2)}$$

4. Calculate the standard error of the mean (S_x). Standard error is inversely proportional to the square root of the number of samples (increasing n from 4 to 16 reduces S_x by 50%) where S_x equals S_b / \sqrt{n} . [Note: The above procedure is for simple random samples. For systematic sampling, the calculation of standard error should follow instructions in Section 6.5 of EPA soil attainment guidance (USEPA, 1989b). For multiple systematic sampling, the equation to calculate unbiased estimate of variance is also available (Gilbert, 1987, p. 97).]

5. Since the concern is only whether the upper limit of a confidence interval is below or above the Act 2 regulatory threshold (RT), the lower confidence limit (LCL) need not be considered. The upper confidence limit (UCL) can be calculated using the one-tailed (one-sided) t values with n-1 degrees of freedom (df) derived from a table of the student's t distribution, $t_{1-\alpha, n-1}$ (Table IV -2).

6. The 95% UCL ($\alpha=0.05$; one-sided) is calculated by using the following formula and substituting the values determined above plus the appropriate t value obtained from the student's t table where UCL equals $\bar{X} + t_{1-\alpha, n-1} * S_x$.

The UCL number resulting from this formula will indicate with a 95% probability that it is either above or below the Act 2 regulatory threshold (RT) developed for the regulated substance subjected to the test.

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8. Calculation of UCL of Mean of a Lognormal Distribution

Following is a step-by-step description of the approach used to calculate confidence limits of arithmetic mean when the distribution of the data set is lognormal. This method is used in risk assessment by EPA (USEPA, 1992d).

1. Transform all sample data X_i to Y_i ($i = 1, 2, \dots, n$) using the natural logarithm function:

$$Y_i = \ln X_i$$

2. Calculate the arithmetic mean of transformed data by dividing the sum of the transformed data by the total number of data:

$$\bar{Y} = (Y_1 + Y_2 + \dots + Y_n) / n$$

3. Calculate the variance (S_y^2) of transformed data by taking the sum of the squares of each data minus the mean and dividing by the degrees of freedom (df, the total number of samples minus one):

$$S_y^2 = [(Y_1 - \bar{Y})^2 + (Y_2 - \bar{Y})^2 + \dots + (Y_n - \bar{Y})^2] / (n-1)$$

4. Calculate the standard deviation (S_y) by taking the square root of the variance (S_y^2):

$$S_y = \sqrt{S_y^2}$$

5. Since the concern is only whether the upper limit of a confidence interval is below or above the Act 2 regulatory threshold (RT), the lower confidence limit (LCL) need not be considered. The upper confidence limit (UCL) can be calculated using the one-tailed (one-sided) $H_{1-\alpha}$ values associated with sample size n from the table of $H_{1-\alpha}$ for computing a one-sided upper 95% confidence limit on a lognormal mean.

6. The 95% UCL ($\alpha=0.05$; one-sided) is calculated by using the following formula and substituting the values determined above plus the appropriate $H_{1-\alpha}$ value obtained from the table of $H_{1-\alpha}$ where UCL equals

$$\exp\left(\bar{Y} + 0.5 * S_y^2 + S_y * H_{1-\alpha} / \sqrt{n-1}\right).$$

The UCL number resulting from this formula will indicate with a 95% probability that it is either above or below the Act 2 regulatory threshold (RT) developed for the regulated substance subjected to the test.

Note: The $H_{1-\alpha}$ tables can be found in "Selected Tables in Mathematical Statistics, Volume III, American Mathematical Society," pp. 385-419, C. E. Land, 1975. A subset of Land's tables also can be found in "Statistical Methods

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for Environmental Pollution Monitoring,” Tables A10-A13, R. O. Gilbert, 1987. The value of $H_{1-\alpha}$ depends on Sy , n , and the confidence level α . If $H_{1-\alpha}$ is required for values of Sy and n not given in the tables, Land (1975) indicated that four-point Lagrangian interpolation appeared to be adequate with these tables.

The equation used in four-point Lagrangian interpolation is:

$$y = f(x) = \frac{y_1(x-x_2)(x-x_3)(x-x_4)}{(x_1-x_2)(x_1-x_3)(x_1-x_4)} + \frac{(x-x_1)y_2(x-x_3)(x-x_4)}{(x_2-x_1)(x_2-x_3)(x_2-x_4)} + \frac{(x-x_1)(x-x_2)y_3(x-x_4)}{(x_3-x_1)(x_3-x_2)(x_3-x_4)} + \frac{(x-x_1)(x-x_2)(x-x_3)y_4}{(x_4-x_1)(x_4-x_2)(x_4-x_3)}$$

where $y_1 = f(x_1)$

$$y_2 = f(x_2)$$

$$y_3 = f(x_3)$$

$$y_4 = f(x_4)$$

The interpolation procedure may include four interpolation steps which are performed along the columns of the table and one interpolation step performed along the rows of the table. The following example illustrates the procedure to apply the four-point Lagrangian interpolation:

$H_{1-\alpha}$	Sample Size, n			
Table	3	5	7	10
0.1	2.750	2.035	1.886	1.802
0.2	3.295	2.198	1.992	1.881
Sy 0.3	4.109	2.402	2.125	1.977
0.4	5.220	2.651	2.282	2.089

The above table only provides values for sample sizes of 3, 5, 7, and 10, and Sy values of 0.1, 0.2, 0.3 and 0.4. To interpolate a value for a sample size of 6 and an Sy value of 0.25, the first step is to interpolate a value corresponding to an Sy of 0.25 and a sample size of 3 using the four-point Lagrangian interpolation equation, where

$$x = 0.25$$

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$$\underline{x_1} = 0.10 \quad \underline{y_1} = 2.750$$

$$\underline{x_2} = 0.20 \quad \underline{y_2} = 3.295$$

$$\underline{x_3} = 0.30 \quad \underline{y_3} = 4.109$$

$$\underline{x_4} = 0.40 \quad \underline{y_4} = 5.220$$

The result of this interpolation step is $\underline{y} = \underline{f(0.25)} = 3.667$.

The second step is to interpolate a value corresponding to S_y of 0.25 and a sample size of 5 using the four-point Lagrangian interpolation equation, where

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$$\underline{x} = 0.25$$

$$\underline{x}_1 = 0.10 \quad \underline{y}_1 = 2.035$$

$$\underline{x}_2 = 0.20 \quad \underline{y}_2 = 2.198$$

$$\underline{x}_3 = 0.30 \quad \underline{y}_3 = 2.402$$

$$\underline{x}_4 = 0.40 \quad \underline{y}_4 = 2.651$$

The result of this interpolation step is $\underline{y} = \underline{f(0.25)} = 2.295$.

The third step is to interpolate a value corresponding to an S_y of 0.25 and a sample size of 7 using the four-point Lagrangian interpolation equation, where

$$\underline{x} = 0.25$$

$$\underline{x}_1 = 0.10 \quad \underline{y}_1 = 1.886$$

$$\underline{x}_2 = 0.20 \quad \underline{y}_2 = 1.992$$

$$\underline{x}_3 = 0.30 \quad \underline{y}_3 = 2.125$$

$$\underline{x}_4 = 0.40 \quad \underline{y}_4 = 2.282$$

The result of this interpolation step is $\underline{y} = \underline{f(0.25)} = 2.055$.

The fourth step is to interpolate a value corresponding to an S_y of 0.25 and a sample size of 10 using the four-point Lagrangian interpolation equation, where

$$\underline{x} = 0.25$$

$$\underline{x}_1 = 0.10 \quad \underline{y}_1 = 1.802$$

$$\underline{x}_2 = 0.20 \quad \underline{y}_2 = 1.881$$

$$\underline{x}_3 = 0.30 \quad \underline{y}_3 = 1.977$$

$$\underline{x}_4 = 0.40 \quad \underline{y}_4 = 2.089$$

The result of this interpolation step is $\underline{y} = \underline{f(0.25)} = 1.927$.

The last step is using the results obtained from steps 1 - 4 to perform another four-point Lagrangian interpolation to generate a value corresponding to an S_y of 0.25 and a sample size of 6, where

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$$\underline{x} = 6$$

$$\underline{x}_1 = 3 \quad \underline{y}_1 = 3.667$$

$$\underline{x}_2 = 5 \quad \underline{y}_2 = 2.295$$

$$\underline{x}_3 = 7 \quad \underline{y}_3 = 2.055$$

$$\underline{x}_4 = 10 \quad \underline{y}_4 = 1.927$$

The resulted interpolation value is 2.087.

9. Procedure and Example for Conducting the Wilcoxon Rank Sum Test

Procedure

For each cleanup unit and pollution parameter, use the following procedure to compute the WRS test statistic and to determine on the basis of that statistic if the cleanup unit being compared with the background reference area has attained the background standard.

1. Collect the m samples in the reference area and the n samples in the cleanup unit ($m + n = N$).
2. Measure each of the N samples for the pollution parameter of interest.
3. Consider all N data as one data set. Rank the N data from 1 to N ; that is, assign the rank 1 to the smallest datum, the rank 2 to the next smallest datum, ..., and the rank N to the largest datum.
4. If several data are tied, *i.e.*, have the same value, assign them the midrank, that is, the average of the ranks that would otherwise be assigned to those data.
5. If some of the reference-area and/or cleanup-unit data are less-than data (*i.e.*, data less than the limit of detection) consider these less-than data to be tied at a value less than the smallest measured (detected) value in the combined data set. Assign the midrank for the group of less-than data to each less-than datum. For example, if there were 10 less-than data among the background reference and cleanup-unit measurements, they would each receive the rank 5.5, which is the average of the ranks from 1 to 10. The assumption that all less-than measurements are less than the smallest detected measurement should not be made lightly because it may not be true for some pollution parameters, as pointed out by Lambert et al. (1991). However, the development of statistical testing procedures to handle this situation are beyond the scope of this document.

The above procedure is applicable when all measurements have the same limit of detection. When there are multiple limits of detection, the adjustments given in Millard and Deveral (1988) may be used.

Do not compute the WRS test if more than 40% of either the reference-area or cleanup unit measurements are less-than values. However, still conduct the Quantile test.

6. Sum the ranks of the n samples from the cleanup unit. Denote this sum by W_{rs} .

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7. If both m and n are less than or equal to 10 and no ties are present, conduct the test of H_0 (cleanup standard attained, $Pr = 1/2$) versus H_a (cleanup standard not attained, $Pr > 1/2$) by comparing W_{rs} to the appropriate critical value in Table A.5 in Hollander and Wolfe (1973). Then go to Step 12 below.

8. If both m and n are greater than 10, go to Step 9. If m is less than 10 and n is greater than 10, or if n is less than 10 and m is greater than 10, or if both m and n are less than or equal to 10 and ties are present, then consult a statistician to generate the required tables.

9. If both m and n are greater than 10 and ties are not present, compute Equation A3-1 and go to Step 11.

$$Z_{rs} = \frac{W_{rs} - n(N+1)/2}{\sqrt{mn(N+1)/12}} \quad (\text{A3-1})$$

10. If both m and n are greater than 10 and ties are present, compute

$$Z_{rs} = \frac{W_{rs} - n(N+1)/2}{\sqrt{(nm/12) \left[N+1 - \sum_{j=1}^g t_j(t_j^2 - 1) / (N(N-1)) \right]}} \quad (\text{A3-2})$$

where g is the number of tied groups and t_j is the number of tied measurements in the j th group.

11. Reject H_0 (cleanup standard attained) and accept H_a (cleanup standard not attained) if Z_{rs} (from Equation A3-1 or A3-2, whichever was used) is greater than or equal to $Z_{1-\alpha}$, where $Z_{1-\alpha}$ is the value that cuts off $100\alpha\%$ of the upper tail of the standard normal distribution.

12. If H_0 is not rejected, conduct the Quantile test.

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EXAMPLE

TESTING PROCEDURE FOR THE WILCOXON RANK SUM TEST

1. Suppose that the number of samples was determined using the following specification:

β = specified Type II error rate = 0.30

α = specified Type I error rate = 0.05

c = specified proportion of the total number of required samples, N , that will be collected in the reference area = 0.50

Pr = specified probability greater than 1/2 and less than 1.0 that a measurement of a sample collected at a random location in the cleanup unit is greater than a measurement of a sample collected at a random location in the reference area = 0.75

R = expected rate of missing or unusable data = 0.10

For these specifications we found that $m = n = 14$ based on Noether's formula.

2. Rank the reference-area and cleanup-unit measurements from 1 to 28, arranging the data and their ranks as illustrated. Measurements below the limit of detection are denoted by ND and assumed to be less than the smallest value reported for the combined data sets. The data are lead measurements (mg/kg).

5.3. The sum of the ranks of the cleanup unit is

$$W_{rs} = 3 + 7 + \dots + 27 + 28 = 272.$$

4. Compute Z_{rs} using Equation A3-2 because ties are present. There are $t = 5$ tied values for the $g = 1$ group of ties (ND values). We obtained:

$$\begin{aligned} Z_{rs} &= \frac{272 - 14(28 + 1) / 2}{\sqrt{(14 * 14 / 12) [28 + 1 - 5(5 * 5 - 1) / (28(28 - 1))]} } \\ &= \frac{69}{21.704} = 3.18 \end{aligned}$$

5. From the table of z (Table IV-3) we find that $Z_{1-\alpha} = 1.645$ for $\alpha = 0.05$ ($\alpha = 0.05$, the Type I error rate for the test, was specified in Step 1 above). Since $3.18 > 1.645$, we reject the null hypothesis $H_0: Pr = 1/2$ and accept the alternative hypothesis $H_a: Pr > 1/2$.
6. Conclusion:
The cleanup unit does not attain the cleanup standard of $Pr = 1/2$. This

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test result occurred because most of the small ranks were for the reference area and most of the large ranks were for the cleanup unit. Hence, W_{rs} was large enough for H_0 to be rejected.

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Example - Wilcoxon Rank Sum Test

Reference Area		Cleanup Unit	
Data	Rank	Data	Rank
ND	3		
ND	3	ND	3
ND	3		
ND	3		
39	6		
		48	7
49	8		
		51	9
53	10		
59	11		
61	12		
65	13		
67	14		
70	15		
72	16		
75	17		
		80	18
		82	19
		89	20
		100	21
		150	22
		164	23
		193	24
		208	25
		257	26
		265	27
		705	28
		Wrs = 272	

10. Procedure and Example for Conducting the Quantile Test

Table Look-Up Procedure

A simple table look-up procedure for conducting the Quantile test when m and n are specified *a priori* is given in this section. It is assumed that m and n representative measurements have been obtained from the reference area and the cleanup unit, respectively. The procedure in this section is approximate because the Type I error rate, α , of the test may not be exactly what is required. However, the difference between the actual and required levels will usually be small. Moreover, the exact α level may be computed.

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The testing procedure is as follows:

1. Specify the required Type I error rate, α . The available options in this document are α equal to 0.01, 0.025, 0.05 and 0.10.
- ~~4.2.~~ Turn to Table A.6, A.7, A.8, or A.9 in Appendix A of EPA 1992 guidance document (USEPA, 1992c) if α is 0.01, 0.025, 0.05, or 0.10, respectively.
- ~~5.3.~~ Enter the selected table with m and n (the number of reference-area and cleanup-unit measurements, respectively) to find
 - values of r and k needed for the Quantile test.
 - actual α level for the test for these values of r and k (the actual α may differ slightly from the required a level in Step 1)
- ~~6.4.~~ If the table has no values of r and k for the values of m and n , enter the table at the closest tabled values of m and n . In that case, the α level in the table will apply to the tabled values of m and n , not the actual values of m and n . However, the α level for the actual m and n can be computed using the following equations:

$$\alpha = \frac{\sum_{i=k}^r \left(\frac{m+n-r}{n-i} \right) \binom{r}{i}}{\binom{m+n}{n}} \quad (\text{A4-1})$$

$$\text{where } \binom{a}{b} \equiv \frac{a!}{b!(a-b)!}$$

$$\text{and } a! = a * (a-1) * (a-2) * \dots * 3 * 2 * 1$$

- ~~7.5.~~ Order from smallest to largest the combined $m + n = N$ reference-area and cleanup-unit measurements for the pollution parameter. If measurements less than the limit of detection are present in either data set, assume that their values are less than the r th largest measured value in the combined data set of N measurements (counting down from the maximum measurement). If fewer than r measurements are greater than the limit of detection, then the Quantile test cannot be performed.
- ~~8.6.~~ If the r th largest measurement (counting down from the maximum measurement) is among a group of tied (equal-in-value) measurements, then increase r to include that entire set of tied measurements. Also increase k by the same amount. For example, suppose from Step 3 we have $r = 6$ and $k = 6$. Suppose the 5th through 8th largest measurements

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(counting down from the maximum measurement) have the same value. Then we would increase both r and k from 6 to 8.

- ~~9.7.~~ Count the number, k , of measurements from the cleanup unit that are among the r largest measurements of the ordered N measurements, where r and k were determined in Step 3 (or Step 6 if the r th largest measurement is among a group of tied measurements).
- ~~10.8.~~ If the observed k (from Step 7) is greater than or equal to the tabled value of k , then reject H_0 and conclude that the cleanup unit has not attained the reference area cleanup standard ($\varepsilon = 0$ and $\Delta/\sigma = 0$).
- ~~11.9.~~ If H_0 is not rejected, then do the WRS test. If the WRS test indicates the H_0 should be rejected, then additional remedial action may be necessary.

EXAMPLE

TABLE LOOK-UP TESTING PROCEDURE FOR THE QUANTILE TEST

1. We illustrate the Quantile test using the measurements listed in the example of [Attachment 3 Section IV.B.9](#). There are 14 measurements in both the reference area and the cleanup unit. Suppose we specify $\alpha = 0.05$ for this Quantile test.
2. Turn to Table A.8 in USEPA 1992 guidance (USEPA, 1992c; because the table is for $\alpha = 0.05$). We see that there are no entries in that table for $m = n = 14$. Hence, we enter the table with $n = m = 15$, the values closest to 14. For $n = m = 15$ we find $r = 4$ and $k = 4$. Hence, the test consists of rejecting the H_0 if all 4 of the 4 largest measurements among the 28 measurements are from the cleanup unit.
3. The $N = 28$ largest measurements are ordered from smallest to largest in the Example of [Section IV.B.9 Attachment 3](#).
4. From the Example of [Section IV.B.9 Attachment 3](#), we see that all 4 of the $r = 4$ largest measurements are from the cleanup unit. That is, $k = 4$.
5. Conclusion:

Because $k = 4$, we reject the H_0 and conclude that the cleanup unit has not attained the cleanup standard of $\varepsilon = 0$ and $\Delta/\sigma = 0$. The Type I error level of this test is approximately 0.05.

Note: The exact Type I error level, α , for this test is not given in Table A.8 in USEPA 1992 guidance (USEPA, 1992c) because the table does not provide r , k , and α for $m = n = 14$. However, the exact α level can be computed using Equation (A4-1).

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Table IV-1. Random Number Table

67	35	39	82	14	21	81	21	96	81	65	41	49	04	80	38	34	13	03	15	96	42	55	62	54
43	25	59	81	92	29	54	98	87	58	77	38	02	09	27	06	83	23	00	90	63	39	04	52	72
93	16	47	22	58	33	01	43	61	70	10	55	75	64	68	40	17	24	98	10	53	93	00	31	43
76	77	01	14	64	62	38	18	48	04	77	42	32	38	34	34	34	91	42	14	98	51	98	29	05
69	46	32	94	85	32	27	87	78	37	73	39	25	48	92	91	57	68	52	55	11	08	99	13	55
79	92	47	00	30	13	95	52	30	16	41	45	60	80	42	90	05	38	89	84	04	33	13	21	72
84	35	41	19	11	63	65	09	06	44	43	71	87	58	78	95	27	91	41	54	10	42	38	55	83
18	57	74	64	75	42	79	88	46	32	90	31	29	09	90	07	59	89	22	74	50	05	90	43	37
14	18	29	77	76	54	35	67	41	92	09	28	91	97	68	05	60	09	22	47	04	96	99	06	24
49	02	18	20	81	94	15	81	23	52	28	84	83	75	19	13	55	96	13	70	49	79	66	85	27
49	44	95	16	39	39	13	83	99	97	38	48	63	01	40	03	95	68	71	39	36	99	24	29	55
62	07	74	32	26	41	64	83	37	57	55	37	51	98	24	99	16	02	88	85	13	65	61	81	59
75	35	06	72	07	45	22	98	59	25	90	22	41	03	96	33	89	33	58	78	01	32	36	92	82
12	50	08	09	64	33	54	62	98	24	41	72	97	33	34	11	73	67	33	79	95	62	31	23	87
16	95	18	38	50	33	78	48	00	83	01	43	77	97	26	74	84	53	05	49	29	75	77	02	32
76	23	56	61	20	15	68	82	18	28	35	82	40	18	40	31	78	53	98	45	21	87	21	31	95
74	26	53	14	97	14	09	11	22	65	74	81	52	44	80	03	86	84	78	02	55	45	90	71	49
93	69	54	96	15	66	92	23	22	51	38	42	26	71	37	01	70	87	82	47	97	83	49	24	10
85	99	75	39	81	83	56	56	87	09	32	47	40	14	72	95	74	21	08	69	47	94	65	84	88
86	43	28	23	92	54	05	55	03	89	12	57	75	16	83	36	93	99	23	59	67	24	69	74	30
22	91	19	64	96	84	66	44	09	48	80	12	65	25	43	76	36	68	27	47	52	35	61	03	33
65	82	01	56	34	08	22	38	56	21	68	55	13	18	97	45	90	91	27	25	92	06	69	84	31
51	41	63	38	07	27	96	11	21	06	24	45	33	45	37	44	40	67	80	81	39	80	77	98	43
97	80	96	04	25	30	36	44	40	25	84	23	42	79	14	41	11	64	23	14	38	29	48	18	65
89	63	32	14	59	33	78	24	52	88	02	79	97	35	74	67	96	31	61	18	00	44	59	88	88
54	14	28	53	79	48	05	74	00	98	15	74	72	91	47	45	90	66	55	38	99	60	85	09	01
77	14	06	84	47	46	88	91	03	36	75	64	77	72	11	96	46	87	33	07	29	48	37	86	66
67	33	09	75	00	76	85	28	80	71	36	29	40	32	52	52	72	89	43	05	89	50	25	84	26
75	48	93	50	88	27	76	21	90	66	48	55	88	37	76	57	00	14	83	60	67	20	35	37	18
75	86	22	20	23	27	17	67	16	38	16	33	28	72	13	47	84	57	36	12	75	86	75	23	51
40	41	19	44	32	22	13	31	25	77	28	93	89	37	04	52	71	49	87	72	32	30	69	94	36
70	94	88	25	57	99	94	82	56	91	38	22	09	52	01	84	00	60	04	91	53	10	10	51	94
42	06	41	49	47	44	71	23	61	25	64	16	16	04	48	20	65	84	89	71	43	89	73	79	80
90	55	23	36	61	93	34	69	43	83	38	03	93	00	03	13	04	77	54	90	61	26	88	01	26
22	71	21	14	59	41	29	51	06	96	62	92	63	96	16	62	48	56	86	21	16	58	33	07	41
65	63	59	60	55	36	77	10	63	48	11	60	55	27	52	73	11	95	03	79	46	12	07	26	52
74	20	65	77	78	83	37	34	09	07	47	57	86	13	47	91	17	32	50	29	72	25	87	96	71
12	16	90	59	89	14	66	72	99	45	88	86	45	48	35	26	30	34	73	46	78	29	91	46	44
52	14	41	65	84	73	55	53	00	76	43	83	09	28	13	82	07	62	72	74	60	34	43	69	26
19	87	80	56	89	83	28	45	99	87	37	02	53	39	74	08	91	23	30	13	59	59	10	57	10
29	13	62	89	16	81	78	54	60	92	31	01	04	83	60	16	42	66	81	37	42	39	74	64	40
37	30	72	00	39	53	83	30	75	48	44	30	38	98	76	94	55	60	35	12	22	82	36	18	48
66	17	13	28	82	64	10	76	67	69	53	39	05	71	22	35	13	39	97	27	48	26	94	74	53
86	41	73	49	70	03	41	05	77	28	37	71	01	30	86	36	42	65	97	78	09	34	36	56	01
56	52	43	82	45	20	20	45	49	83	52	73	63	70	47	89	93	77	32	26	73	70	50	75	10
17	89	69	72	84	80	48	78	32	51	66	12	29	79	90	25	11	33	37	44	25	47	18	40	74
11	29	91	99	26	43	90	15	09	64	20	54	89	91	59	01	93	40	33	04	46	91	86	33	90
96	68	63	61	19	29	71	05	42	14	05	84	10	36	27	60	49	40	84	92	29	23	10	45	05
29	12	44	07	75	41	74	25	36	05	49	36	50	27	64	37	51	92	47	32	05	02	21	20	71
79	00	54	24	24	32	03	96	86	98	90	65	41	87	39	29	39	75	07	20	14	94	28	87	23

EXAMPLE

USING THE RANDOM NUMBER TABLE

Say, we need to select 10 random numbers with four digits between 0000 and 6000. We need to select a starting point on the table and a path to be followed. The common way to locate a starting point is to look away and arbitrarily point to a starting point. Suppose the number we located this way was 3848. (It is located in the upper left corner of the block that is in the third large block from the left and the third large block down.) From here we will proceed down the column, then go to the top of the next set of columns, if necessary. The first selected number is 3848. Proceeding down the column, we find 5537 next. This is the second selected number. The number 9022 is next. This number is discarded. Continue down this column, the selected 10 random numbers will be 3848, 5537, 4172, 0143, 3582, 3842, 3247, 1257, 2445, and 0279. (The numbers 9022, 7481, 8012, 6855 and 8423 were discarded because they are greater than 6000.)

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Table IV-2. Student's t-Distribution for Selected Alpha and Degrees of Freedom

		a for determining $t_{1-\alpha, n-1}$							
one-tailed	0.450	0.250	0.200	0.100	0.050	0.025	0.010	0.005	
		a for determining $t_{1-\alpha/2, n-1}$							
two-tailed	0.900	0.500	0.400	0.200	0.100	0.050	0.020	0.010	
df	1	0.158	1.000	1.376	3.078	6.314	12.706	31.821	63.657
	2	0.142	0.816	1.061	1.886	2.920	4.303	6.925	9.925
	3	0.137	0.765	0.978	1.638	2.353	3.182	4.541	5.841
	4	0.134	0.741	0.941	1.533	2.132	2.776	3.747	4.604
	5	0.132	0.727	0.920	1.476	2.015	2.571	3.365	4.032
	6	0.131	0.718	0.906	1.440	1.943	2.447	3.143	3.707
	7	0.130	0.711	0.896	1.415	1.895	2.365	2.998	3.499
	8	0.130	0.706	0.889	1.397	1.860	2.306	2.896	3.355
	9	0.129	0.703	0.883	1.383	1.833	2.262	2.821	3.250
	10	0.129	0.700	0.879	1.372	1.812	2.228	2.764	3.169
	11	0.129	0.697	0.876	1.363	1.796	2.201	2.718	3.106
	12	0.128	0.695	0.873	1.356	1.782	2.179	2.681	3.055
	13	0.128	0.694	0.870	1.350	1.771	2.160	2.650	3.012
	14	0.128	0.692	0.868	1.345	1.761	2.145	2.624	2.977
	15	0.128	0.691	0.866	1.341	1.753	2.131	2.602	2.947
	16	0.128	0.690	0.865	1.337	1.746	2.120	2.583	2.921
	17	0.128	0.689	0.863	1.333	1.740	2.110	2.567	2.898
	18	0.127	0.688	0.862	1.330	1.734	2.101	2.552	2.878
	19	0.127	0.688	0.861	1.328	1.729	2.093	2.539	2.861
	20	0.127	0.687	0.860	1.325	1.725	2.086	2.528	2.845
	21	0.127	0.686	0.859	1.323	1.721	2.080	2.518	2.831
	22	0.127	0.686	0.858	1.321	1.717	2.074	2.508	2.819
	23	0.127	0.685	0.858	1.319	1.714	2.069	2.500	2.807
	24	0.127	0.685	0.857	1.318	1.711	2.064	2.492	2.797
	25	0.127	0.684	0.856	1.316	1.708	2.060	2.485	2.787
	26	0.127	0.684	0.856	1.315	1.706	2.056	2.479	2.779
	27	0.127	0.684	0.855	1.314	1.703	2.052	2.473	2.771
	28	0.127	0.683	0.855	1.313	1.701	2.048	2.467	2.763
	29	0.127	0.683	0.854	1.311	1.699	2.045	2.462	2.756
	30	0.127	0.683	0.854	1.310	1.697	2.042	2.457	2.750
	40	0.126	0.681	0.851	1.303	1.684	2.021	2.423	2.704
	60	0.126	0.679	0.848	1.296	1.671	2.000	2.390	2.660
	120	0.126	0.677	0.845	1.289	1.658	1.980	2.358	2.617

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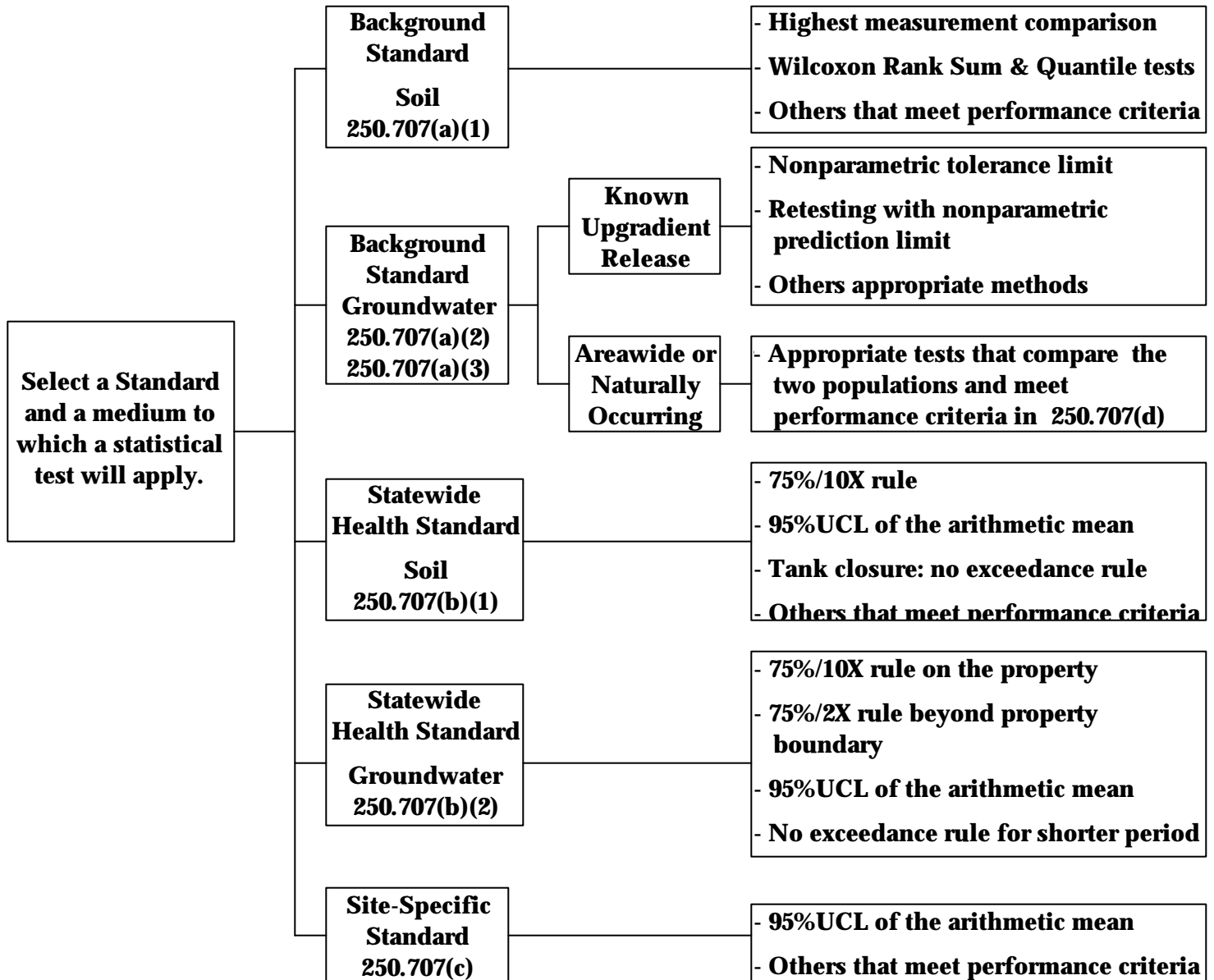
∞ 0.126 0.674 0.842 1.282 1.645 1.960 2.326 2.576

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Table IV-3 Table of z for Selected Alpha

α	$Z_{1-\alpha}$
0.450	0.124
0.400	0.253
0.350	0.385
0.300	0.524
0.250	0.674
0.200	0.842
0.100	1.282
0.050	1.645
0.025	1.960
0.010	2.326
0.0050	2.576
0.0025	2.807
0.0010	3.090

Figure IV-1. Flow Chart of Recommended Statistical Methods



C. Mass Calculations

1. Groundwater Mass Calculation

Calculate Water Volume (WV)

Water Volume(WV-ft³) = Length of plume(L) x Average Thickness of plume(H) x Average Width of plume(W) x porosity(n)

Calculate Water Mass (WM)

Water Mass(WM-lb.) = Water Volume(WV-ft³) x 62.5 lb./ft³

Calculate Mass of Contaminant

Water Mass(WM-lb.) x Contaminant Concentration(C-ppm) / 10⁶ =
Contaminant Mass(lb.)

2. Soil Mass Calculation

These soil mass calculations provide a way of quantifying contaminants in soil that under an Act 2 remediation would track the estimations of the mass of contaminants removed from public exposure as a measure of program success. Contaminants removed from public exposure can be any one or a combination of excavation & disposal, treatment or pathway elimination measures. The mass calculations would not include areas of the "site" which site characterization is found at or below the applicable standard. This area remains unchanged and thus there is no reduction in exposure as part of the remediation.

$$M(x) = D_{(soil)} \times V_{(total)} \times C_{ave.}(x)$$

Where:

M(x) = The mass of a specific contaminant in soil (lb)

D_(soil) = Density of soil, assume to be a default value of 110 lb/ft³

V_(total) = Volume based on the soil site characterization data with respect to the horizontal and vertical depth of the soil samples collected in areas above the applicable standard. The volume sum of the each plot would equate to the total volume.

C_{ave. (x)} = The soil contaminant concentration would be the arithmetic mean concentration of the contaminant throughout the soil column. This is the free and

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absorbed phase of the soil contaminant in areas above the applicable standard and expressed in $\text{lb}_{\text{contaminant}}/\text{lb}_{\text{soil}}$ ($\text{ppmw} = \text{ppm}/10^6$).

D. Post-Remediation Care

1. Introduction

This section provides general guidelines on the methodology of post-remediation care and the post-remediation care plan. The plan shall be submitted as part of the final report and approved by the Department. The approved post-remediation care plan will become a condition of attainment of the chosen standard(s) under Act 2. The plan shall identify the activities that will be conducted after closure and the frequency of those activities.

Answer the questions from the matrix in Table IV-4, relative to your chosen standard(s), to determine when a post-remediation care plan is required. The proposed post-remediation care requirements shall be included in the cleanup plan for Department approval, as specified in Section 250.410(b)(5).

If any of the above answers are yes, relative to the selected standard(s), a post-remediation care plan shall be included as part of the final report.

2. Institutional versus Engineering Controls

An institutional control, by definition of Act 2, is a measure taken to limit or prohibit certain activities that may interfere with the integrity of a remedial action or result in exposure to regulated substances at a site. These include, but are not limited to, fencing or restrictions on the future use of the site.

An engineering control, by definition of Act 2, is a remedial action directed exclusively toward containing or controlling the migration of regulated substances through the environment. These include, but are not limited to, slurry walls, liner systems, caps, leachate collection systems and groundwater recovery trenches.

Example: A deed restriction prohibiting use of the property in some way is an institutional control. An impermeable cap that prevents volatilization to the atmosphere, controls contaminant migration by run-on and run-off, and limits dermal contact (hydraulic conductivity less than 1×10^{-7} cm/sec) is an engineering control.

Institutional controls cannot be used to attain the background or Statewide health standards. Institutional controls alone cannot be used to attain the site-specific standard. Engineering and/or institutional controls may be used to maintain all three standards.

3. Post-Remediation Care Plan

The post-remediation care plan should include the following:

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- The reason(s) that the post-remediation care plan is necessary (See Sections 250.204(g), 250.311, 250.312, 250.411(d), and 250.708).
- A schedule of operation and maintenance of the controls. Include a description of the planned maintenance activities and frequencies at which they will be performed and future plans for submission of proposed changes.
- Information regarding the submission of quarterly monitoring results and analysis, or as otherwise approved by the Department, that demonstrates the effectiveness of the remedy. Include a description of the planned monitoring activities and frequencies at which they will be performed.
- The proposed method for reporting any instances of nonattainment of the selected standard(s).
- The proposed measures to be taken to correct nonattainment conditions as they occur. Include a description of the corrective measures that may be required for all possible nonattainment scenarios.
- Information regarding the maintenance of records at the property where the remediation is being conducted for monitoring, sampling and analysis. Include the name, address and telephone number of the person or office to contact about the site during the post-remediation care period. This person or office shall keep an updated post-remediation plan during the post-remediation care period.
- Documentation of a plan to maintain the mitigated ecological resource, report of success or failure of the mitigation measure, and demonstration of sustaining the measures up to five years from final report approval.
- If requested by the Department, documentation of financial ability to implement the remedy and the post-remediation care plan.

4. Post-Remediation Monitoring

In some situations, post-remediation monitoring may be required as part of the post-remediation care program. For example, post-remediation monitoring is conducted to determine any changes in groundwater quality after attainment of a standard(s). Unless otherwise instructed by the Department, analytes to be included are those which were monitored during assessment and remediation monitoring. All monitoring activities should incorporate quality control and quality assurance provisions consistent with Act 2 regulations and policies.

Well locations for post-remediation monitoring are generally selected from existing monitoring wells used in the assessment and remediation phases. Where a source of contamination is removed prior to impacting groundwater, post-remediation monitoring should continue at locations that will detect any residual contamination in the unsaturated zone that might migrate to the groundwater.

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a) Duration

In most cases, post-remediation monitoring requirements will be developed on a case-by-case basis. The factors determining the duration of post-remediation monitoring are the factors that determine whether a post-remediation care plan is necessary.

b) Frequency

As stated in Section 250.204(g) of the regulations, post-remediation monitoring will take place on a quarterly basis unless otherwise approved by the Department. The interval between sampling events should be short enough to allow for response and correction of any problems that may cause nonattainment at the point of compliance.

Factors that could influence the need for an alternative post-remediation monitoring schedule include site size, groundwater velocity, contaminant characteristics and the vulnerability of a site to pulses of contaminant migration during precipitation events.

c) Cessation of Post-Remediation Monitoring

Post-remediation monitoring may be terminated when monitoring provisions set forth in the post-remediation care plan are met, the engineering controls are no longer needed, and it can be documented by fate and transport analysis that the standard will not be exceeded in the future.

5. Post-Remediation Care Attainment

A person may terminate post-remediation care as approved in the final report if he can demonstrate attainment of the standard(s) without the engineering controls in place, and document a fate and transport analysis that shows the standard will not be exceeded in the future. An amendment to the post-remediation care plan shall be submitted for approval by the Department. The post-remediation care plan shall be amended whenever changes in operating plans or facility design, or events that occur during post-remediation care, affect the currently approved post-remediation care plan.

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TABLE IV-4

Post-Remediation Care Decision Matrix

Background

		Yes	No
1.)	Is an ENGINEERING CONTROL(s) needed to <u>attain and/or maintain</u> the background standard?		
2.)	Is an INSTITUTIONAL CONTROL(s) needed to <u>maintain</u> the background standard?		
3.)	Does the FATE & TRANSPORT analysis indicate that the background standard may be exceeded at the point of compliance in the future?		
4.)	Does the remediation rely on NATURAL ATTENUATION?		

Statewide Health

1.)	Is an ENGINEERING CONTROL(s) needed to <u>attain and/or maintain</u> the Statewide health standard?		
2.)	Is an INSTITUTIONAL CONTROL(s) needed to <u>maintain</u> the Statewide health standard?		
3.)	Does the FATE & TRANSPORT analysis indicate that the Statewide health standard, <u>including the solubility limitation in section 250.304(b)</u> , may be exceeded at the point of compliance in the future?		
4.)	Does the remediation rely on NATURAL ATTENUATION?		
5.)	If there are ECOLOGICAL IMPACTS identified in the evaluation of ecological receptors that must be addressed, will a post-remedy use be relied on to eliminate complete exposure pathways,		

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as set forth in Section 250.311(e)(2)?

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6.)	If there are ECOLOGICAL IMPACTS identified in the evaluation of ecological receptors that must be addressed, will mitigation measures be implemented, as set forth in section 250.311(f)(v)? [If yes, follow guidelines in section 250.312(b)(1-3) for reporting requirements.]		
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Site-Specific

1.)	Is an ENGINEERING CONTROL(s) needed to <u>maintain</u> the Site-specific Standard?		
2.)	Is an INSTITUTIONAL CONTROL(s) needed to <u>maintain</u> the Site-specific Standard?		
3.)	Does the FATE & TRANSPORT analysis indicate that the Site-specific Standard may be exceeded at the point of compliance in the future?		
4.)	Does the remediation rely on NATURAL ATTENUATION?		
5.)	If there are ECOLOGICAL IMPACTS identified in the evaluation of ecological receptors that must be addressed, will a post-remedy use be relied on to eliminate complete exposure pathways, as set forth in section 250.311(e)(2)?		
6.)	If there are ECOLOGICAL IMPACTS identified in the evaluation of ecological receptors that must be addressed, will mitigation measures be implemented, as set forth in section 250.311(f)? [If yes, follow guidelines in section 250.411(f)(1-3) for reporting requirements.]		