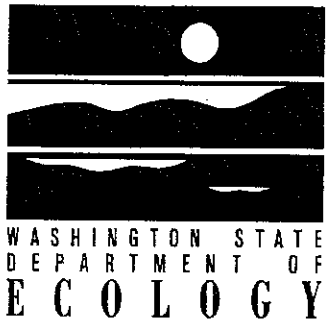

Washington State Department of Ecology
Toxics Cleanup Program

Guidance on Sampling and Data Analysis Methods

January 1995
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DEPARTMENT OF ECOLOGY

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January 9, 1995

TO: Interested Parties

FROM: Mary E Burg, Program Manager
Toxics Cleanup Program

SUBJECT: Guidance on Sampling and Data Analysis Methods

Attached is the January 1995 edition of the Department of Ecology's *Guidance on Sampling and Data Analysis Methods*. Because of the complex technical and policy issues involved, this guidance is expected to be an evolving document. Ecology will periodically evaluate the need for revisions after considering written comments received from interested parties and the experiences of agency staff in implementing the guidance.

One of the most common questions Ecology receives on sampling is, "how many soil samples should be collected for a site investigation?" Ecology does not have numerical requirements or tables for determining the number of samples to collect. This is a site-specific problem that requires the application of professional judgment using the procedures provided in this guidance (see Section A1 0 in Appendix I). Questions regarding this guidance should be directed to a Toxics Cleanup Program staff member at the appropriate Ecology regional office:

Northwest:	(206) 649-7000 (Voice) or (206) 649-4259 (TDD)
Southwest	(206) 704-6300 (Voice) or (206) 407-6306 (TDD)
Central	(509) 575-2491 (Voice) or (509) 454-7673 (TDD)
Eastern	(509) 456-2926 (Voice) or (509) 458-2055 (TDD)

An earlier version of the attached document has been referenced in other Ecology documents. You should consider using the attached document when performing actions using the Ecology publications: *Guidance for Clean Closure of Dangerous Waste Facilities* (August, 1994) and *Guidance for Remediation of Petroleum Contaminated Soils* (April, 1994). The *Guidance for Clean Closure of Dangerous Waste Facilities* (August, 1994) references this guidance under the title, *Sampling and Data Analysis Issues for Ecology Staff to Consider in Reviewing Independent Remediation Reports*.

Your written comments on this document and requests to be placed on the mailing list for Guidance updates and related mailings should be addressed to:

Department of Ecology
Toxics Cleanup Program
Policy Section
Sampling and Statistical Guidance
P.O. Box 47600
Olympia, WA 98504-7600

Washington State Department of Ecology

Guidance on Sampling and Data Analysis Methods

Toxics Cleanup Program
PO Box 47600
Olympia, WA 98504-7600

January 1995

Disclaimer

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Introduction

This document provides guidance for cleanup actions conducted under the Model Toxics Control Act Cleanup Regulation, Chapter 173-340 WAC. It is intended for use in preparing sampling plans, in preparing reports for submittal to the Washington Department of Ecology, and in the review of reports by Ecology staff.

To assist in the preparation of sampling plans, guidance is provided on common sampling and data analysis issues. "Data analysis" means the numerical analysis of sampling results to determine whether cleanup levels have been met, to plan a cleanup, to determine whether a cleanup was successful, or to support other decisions relating to the investigation and cleanup of contaminated soil or groundwater.

For reports on cleanup actions, this document discusses issues to consider in reviewing the adequacy of the report before it is submitted to Ecology, and includes information that should be studied before preparing the report.

The scope of this guidance is limited. It is not intended to provide comprehensive coverage of all sampling and data analysis problems that may be encountered in the investigation and cleanup of soil or groundwater. It does not attempt to provide guidance on how to plan a remedial investigation. Issues relating to laboratory analyses of samples and analytical methods are also not discussed.

The document is divided into five parts:

Section 1.0 Provides a brief summary of relevant information, including requirements of the Model Toxics Control Act Cleanup Regulation, Chapter 173-340 WAC and policies relating to sampling and data analysis. A list is provided of relevant implementation guidance presently available from Ecology.

Section 2.0 Discusses issues to consider in reviewing a cleanup action report before submitting it to Ecology.

Section 3.0 Provides information on the use of background data for making cleanup decisions.

Appendix I Provides guidance on sampling procedures for soil and groundwater. Methods for analyzing data obtained using these procedures are provided.

Appendix II Provides selected excerpts from EPA documents cited in this guidance. Ecology guidance on PQLs as Cleanup Standards (Implementation Memo No. 3, dated November 24, 1993) is included.

Petroleum Contaminated Soils.

For the investigation and remediation of petroleum contaminated soils, sampling must comply with the *Guidance for Remediation of Petroleum Contaminated Soils* (Publication No. 91-30, Revised April, 1994). For issues that are not addressed there, use the *Guidance on Sampling and Data Analysis Methods* as a supplement.

Independent Cleanups.

The *Guidance on Sampling and Data Analysis Methods* is intended to facilitate independent cleanups under the Model Toxics Control Act Cleanup Regulation by explaining Ecology's expectations on how sampling of soil and groundwater will be conducted, how the results will be used, and how the relevant information will be reported to Ecology. It should be regarded as a supplement to the *Guidance on Preparing Independent Remedial Action Reports Under the Model Toxics Control Act Chapter 70.105D RCW* (Publication No. 94-18).

For an independent cleanup where it is impracticable to comply with a recommendation in the *Guidance on Sampling and Data Analysis Methods* because of site-specific considerations, or where sampling issues arise that are not covered here, it is expected that best professional judgment will be used. The Independent Remedial Action Report should include an explanation, describing what decision was made on the issue and the reasoning behind the decision.

1.0 Requirements and policies on sampling and data analysis under the Model Toxics Control Act (MTCA) Cleanup Regulation

The MTCA Cleanup Regulation includes specific requirements on some sampling and data analysis issues. Additional policies are described here and in other Ecology documents listed in Section 1.1. Note that some requirements in the MTCA Cleanup Regulation and policies in Ecology guidance differ from procedures used by the U.S. Environmental Protection Agency for Superfund cleanups. Consequently, a report based solely on compliance with Superfund regulations and guidance may not be acceptable to Ecology.

Some important sampling and compliance policies or requirements for MTCA cleanup actions include the following:

(1) For groundwater, compliance with cleanup levels must be demonstrated at each monitoring well.[1]

(2) Composite samples should not be used unless there is adequate justification for doing so.[2]

(3) High contaminant concentrations ("outliers") cannot be excluded unless it can be demonstrated that the value is in error.[3]

(4) Statistical procedures which must be used for demonstrating compliance with cleanup levels and other purposes are described in the Model Toxics Control Act Cleanup Regulation and Ecology document, *Statistical Guidance for Ecology Site Managers* (see Section 1.2). See the following section for further information.

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1 WAC 173-340-720(8)(c)(iv).

2 Problems with the use of composite samples are discussed in Chapter 3 of the *Statistical Guidance for Ecology Site Managers*. However, compositing may be used as a screening step when intensive sampling is conducted to search for small areas of contamination (Appendix I, p. 23).

3 See Section 2.3 of the *Statistical Guidance for Ecology Site Managers*. This policy is consistent with U.S. EPA guidance for Superfund cleanups of groundwater (EPA, 1992, p. 2-27) and soil (EPA, 1989, p. 2-16).

U.S. EPA. 1989. Methods for Evaluating the Attainment of Cleanup Standards - Volume 1: Soils and Solid Media. EPA 230/02-89-042. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC

U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater. EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC.

1.1 The "statistical approach" for demonstrating compliance with a cleanup level

The statistical procedures for demonstrating compliance with a cleanup level are explained in the *Statistical Guidance for Ecology Site Managers* (see Section 1.2). The term "statistical approach" used in this document refers to those procedures. Alternatives to the statistical approach are introduced here for "focused" soil sampling (see Section A2.2 in Appendix I) or "area-wide" subsurface sampling of localized contamination (Section A3.3.2.2).

The statistical approach is summarized below. Other variations of the statistical approach are described in the *Statistical Guidance for Ecology Site Managers* but are not applicable in most cases.

(1) The decision rule for demonstrating compliance with a cleanup level has three parts: (i) upper 95% confidence limit on the true population mean (average)[4] must be less than the cleanup level; (ii) no sample concentration can be more than twice the cleanup level; (iii) less than 10% of the samples can exceed the cleanup level.[5] Statistical guidance and software for use with data analysis is described in Section 1.2.

(2) Ecology's *Statistical Guidance for Ecology Site Managers* requires an analysis to determine the appropriate statistical distribution[6] of the sampling data. The statistical formula for calculating the upper confidence limit depends on which distribution (lognormal, normal) applies. For data that do not fit either distribution, one acceptable solution described in Supplement S-6 of the *Statistical Guidance* is to use the largest value in the data set for comparison with the cleanup level.

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4 For compliance, the "true population mean" (a statistical term), not the sample mean, is the variable of concern. For an explanation of the difference between this mean and the sample mean, see Section 1.1 of the *Statistical Guidance for Ecology Site Managers*.

5 These criteria apply to both soil [WAC 173-340-740(7)(e)] and groundwater [WAC 173-340-720(8)(e)]. They apply to cleanup levels based on chronic or carcinogenic threats. Criteria that apply to cleanup levels based on short-term or acute toxic effects are less often used and are not discussed here. Adjustments to the second and third criteria may be permitted when cleanup level is based on background. See Section 4.3.5 of the *Statistical Guidance for Ecology Site Managers* for more information.

6 See Chapter 5 of the *Statistical Guidance for Ecology Site Managers*. Use of statistical methods that are appropriate for the distribution of sampling data is also required by the MTCA Cleanup Regulation [e.g. WAC 173-340-740(7)(c)(iii)].

1.2 Ecology guidance documents relating to sampling and data analysis

The following guidance documents can be obtained through:

Washington State Department of Ecology
Publications Office
PO Box 47600
Olympia, WA 98504-7600
(360) 407-7472 (Voice) or
(360) 407-6006 (TDD).

Sampling guidance

- For an independent cleanup of petroleum contaminated soil, sampling must comply with the *Guidance for Remediation of Petroleum Contaminated Soils* (Publication No. 91-30). For issues not addressed in that document, use the *Guidance on Sampling and Data Analysis Methods* as a supplement.

- For any independent cleanup, sampling must adequately provide the information required by the *Guidance on Preparing Independent Remedial Action Reports Under the Model Toxics Control Act Chapter 70.105D RCW* (Publication No. 94-18).

- *Guidelines and Specifications for Preparing Quality Assurance Project Plans*. (Publication No. 91-16).

- Sampling guidance provided here in Appendix I.

- Some sampling issues (e.g. compositing samples) discussed in Chapter 3 ("Sampling") of *Statistical Guidance for Ecology Site Managers*. (Publication No. 92-54)

For guidance on laboratory analyses, see:

- PQLs as Cleanup Standards (Implementation Memo No. 3, dated November 24, 1993).
- Analytical methods documents listed in WAC 173-340-830(4).

Data analysis

The following provide assistance with analyzing sampling data for comparison with cleanup levels and with the analysis of background data. Some new policies are described here in Appendix I.

- *Model Toxics Control Act Cleanup Levels and Risk Calculation (CLARC II) Update*. Publication Number 94-145. Provides annually updated MTCA cleanup levels.

- *Statistical Guidance for Ecology Site Managers*. Publication Number 92-54.

Provides guidance on statistical requirements of the Model Toxics Control Act Cleanup Regulation. The original document includes five supplements. Supplement S-6 is a separate document that includes new material as well as some revisions.

- Statistics Software Package (MTCA*Stat*)

Performs statistical calculations required in the *Statistical Guidance for Ecology Site Managers*. This package, with documentation, is available from Ecology and requires Microsoft Excel 4.0 or 5.0 for Windows. No other versions of MTCA*Stat* (e.g., for other software products or Apple computers) are available.

To request a copy of MTCA*Stat* and documentation, send a formatted 3 1/2" or 5 1/4" disk to the address below.

Washington State Department of Ecology
Toxics Cleanup Program
PO Box 47600
Olympia, WA 98504-7600

2.0 Sampling plan and data analysis.

Ecology reviews submitted reports and other documents to assess whether the objectives and scope of work are adequate and whether the data presented and analyses performed are sufficient to support the conclusions reached. See Appendix I for guidance on sampling approaches and data analysis.

A report to Ecology must communicate clearly to be acceptable. Data must be presented in a format that is readily understandable. This is normally best accomplished through graphical presentation of data and it is expected that tabulated data will be clearly presented on maps, graphs and other illustrations.

Raw data are expected to be provided in a format that is easily comprehensible and accessible so that calculations can be readily verified and additional analyses can be performed.

Before submitting a cleanup action report to Ecology, review the following items relating to sampling and data analysis to ensure that they have been addressed in the report:

2.1 Sampling plan design

The report should provide a clear explanation of the basis for the sampling plan used to investigate the site. The objectives should be clearly stated and how the sampling plan met those objectives should be discussed.

2.2 Field sampling procedures

The adequacy of sampling techniques is a critical issue in the review of reports submitted to Ecology. The report must provide details on how samples were collected, handled and analyzed in the laboratory.

2.3 Sampling completion and exceptions

Indicate whether sampling was conducted in accordance with the original sampling plan and describe any exceptions.

2.4 Data analysis

Explain the data analysis methods used, why they were used and reference the relevant sections of Ecology guidance. There must be sufficient information in the report to allow a reviewer to establish that the methods were appropriate for the sampling procedures used and the objectives.

There must also be sufficient information in the report to allow a reviewer to understand how the data were analyzed and to check the calculations.

2.5 Cleanup decisions

The cleanup decision presented in a report to Ecology must be supported by sampling results and data analyses. Such decisions include: whether a cleanup is required and if so, where (e.g., which areas or aquifers); the appropriate cleanup methods; and whether the cleanup was successful.

2.6 Requirements of the MTCA Cleanup Regulation

Review the report to ensure that it meets the requirements in the MTCA Cleanup Regulation for the preparation of sampling and analysis plans as presented below:

WAC 173-340-820 SAMPLING AND ANALYSIS PLANS.

(1) General. A sampling and analysis plan shall be prepared for all sampling activities which are part of investigation and remedial actions unless otherwise directed by the department and except for emergencies. The level of detail required in the sampling and analysis plan may vary with the scope and purpose of the sampling activity. Sampling and analysis plans prepared under an order or decree shall be submitted to the department for review and approval.

(2) Contents. The sampling and analysis plan shall specify procedures which ensure that sample collection, handling, and analysis will result in data of sufficient quality to plan and evaluate remedial actions at the site. Additionally, information necessary to ensure proper planning and implementation of sampling activities shall be included References to standard protocols or procedures manuals may be used provided the information referenced is readily available to the department The sampling and analysis plan shall contain:

(a) A statement on the purpose and objectives of the data collection, including quality assurance and quality control requirements;

(b) Organization and responsibilities for the sampling and analysis activities;

(c) Requirements for sampling activities including:
- (i) Project schedule;
- (ii) Identification and justification of location and frequency of sampling;
- (iii) Identification and justification of parameters to be sampled and analyzed;
- (iv) Procedures for installation of sampling devices;
- (v) Procedures for sample collection and handling, including procedures for personnel and equipment decontamination;
- (vi) Procedures for the management of waste materials generated by sampling activities, including installation of monitoring devices, in a manner that is protective of human health and the environment;
- (vii) Description and number of quality assurance and quality control samples, including blanks and spikes;
- (viii) Protocols for sample labeling and chain of custody; and
- (ix) Provisions for splitting samples, where appropriate.

(d) Procedures for analysis of samples and reporting of results, including:
- (i) Detection or quantification limits;
- (ii) Analytical techniques and procedures;
- (iii) Quality assurance and quality control procedures; and
- (iv) Data reporting procedures, and where appropriate, validation procedures.

(3) Available guidance The department shall make available guidance for preparation of sampling and analysis plans

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3.0 Use of background data under the MTCA Cleanup Regulation

The MTCA Cleanup Regulation details the uses of background data for cleanup decisions. The relevant sections of the regulation are identified in the summary below. If background data are included in a report submitted to Ecology, the following should be considered:

(1) Is the purpose of including such data clearly explained, with references to relevant sections of the MTCA Cleanup Regulation?

(2) Are the data clearly identified as natural or area background values? Are the sample size requirements for these types of background met?

(3) Are the sampling locations appropriate for the represented type of background? (Refer to the definitions of "natural" and "area" background below.)

Requirements relating to background data are described in Sections 3.1 - 3.5.

3.1 Definitions

The MTCA Cleanup Regulation provides for two types of background: **natural** and **area** background. These are defined[7] as follows:

> *"Natural background" means the concentration of a hazardous substance consistently present in the environment which has not been influenced by localized human activities. For example, several metals naturally occur in the bedrock and soils of Washington state due solely to the geologic processes that formed these materials and the concentration of these metals would be considered natural background. Also, low concentrations of some particularly persistent organic compounds such as polychlorinated biphenyls (PCBs) can be found in surficial soils and sediment throughout much of the state due to global use of these hazardous substances. These low concentrations would be considered natural background. Similarly, concentrations of various radionuclides which are present at low concentrations throughout the state due to global distribution of fallout from bomb testing and nuclear accidents would be considered natural background.*
>
> *"Area background" means the concentrations of hazardous substances that are consistently present in the environment in the vicinity of a site which are the result of human activities unrelated to releases from that site.*

[7] WAC 173-340-200

3.2 Sampling locations

If sampling is conducted to establish natural or area background, the sampling locations selected should be consistent with the definitions given as follows:

> *For purposes of defining background concentrations, samples shall be collected from areas that have the same basic characteristics as the medium of concern at the site, have not been influenced by releases from the site and, in the case of natural background concentrations, have not been influenced by releases from other localized human activities.*[8]

For sites where Ecology has formal involvement, sampling and analysis work plans for work to develop site-specific background values must be submitted for Ecology's review and approval.

Information on natural background values for some metals is available in the following Ecology publication which can be obtained from the address given in Section 1.2:

Natural Background Soil Metals Concentrations in Washington State. Publication Number 94-115. (Aluminum, arsenic, beryllium, cadmium, chromium, copper, iron, mercury, manganese, nickel, lead and zinc.)

3.3 Number of samples

The number of samples required to establish natural or area background are as follows:

> *When determining natural background concentrations, a sample size of ten or more background soil samples shall be required. When determining area background concentrations, a sample size of twenty or more soil samples shall be required. The number of samples for other media shall be sufficient to provide a representative measure of background concentrations and shall be determined on a case-by-case basis.*[9]

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[8] WAC 173-340-708(11)(b)

[9] WAC 173-340-708(11)(d)

3.4 Calculating a background value

Statistical methods for calculating a background value from sampling data are described in Ecology's *Statistical Guidance for Ecology Site Managers*.[10] Because of the complexity of the calculations, use of MTCA*Stat* to perform the analyses is strongly recommended (see Section 1.2).

3.5 Applications for natural and area background concentrations

Under the MTCA Cleanup Regulation, **natural** background can be used for the following purposes:

(1) To establish a Method A cleanup level for hazardous substances that are not addressed under applicable state or federal laws, or in Tables 1, 2, or 3 of the MTCA Cleanup Regulation.[11]

(2) If a Method A, B, or C cleanup level is a lower concentration than natural background, the cleanup level can be established at a concentration equal to the natural background concentration.[12]

(3) Natural background is one of the factors which can be considered when eliminating individual hazardous substances from further consideration as an indicator substance.[13]

Under the MTCA Cleanup Regulation, **area** background can be used for the following purposes:

(1) To establish a Method C cleanup level equal to the area background concentration where Method A or B cleanup levels are below area background concentrations, unless a more stringent requirement applies.[14]

(2) Area background can be a consideration in the development of a cleanup action plan:

> *When area background concentrations would result in recontamination of the site to levels which exceed cleanup levels, that portion of the cleanup action which addresses cleanup below area background concentrations may be delayed until the off-site sources of hazardous substances are controlled. In these cases the remedial action shall be considered an interim action until cleanup levels are attained.*[15]

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[10] Supplement S-6 of the *Statistical Guidance* includes some revisions to the statistical methods for analyzing background data.

[11] WAC 173-340-700(3)(a)

[12] WAC 173-340-700(4)(d)

[13] WAC 173-340-708(2)

[14] WAC 173-340-706(1). Note that there are stringent criteria for using Method C to establish a cleanup level.

[15] WAC 173-340-360(6)(c)

APPENDIX I

Sampling and Data Analysis

This guidance primarily concerns sampling issues. Brief explanations are provided on data analysis subjects that are discussed in detail in the *Statistical Guidance for Ecology Site Managers*. In addition, some further guidance on data analysis is provided here that is not found in that document. These additions are identified in footnotes as "New compliance guidance".

Contents Summary

A1.0 SOIL SAMPLING

The following guidance provides approaches for sampling and data analysis (Table 1) that are considered generally acceptable to Ecology. However, there may be other approaches that are also acceptable if the approach, and the reasons for using it, are adequately explained in the report and if it is consistent with requirements of the MTCA Cleanup Regulation. When sampling plans are based on other approaches from the technical literature, a copy of the relevant material should be included as an appendix to the report to expedite review. Statisticians or others with similar expertise can be helpful in designing efficient and cost-effective sampling plans. However, it is essential that they have a thorough understanding of the requirements of the MTCA Cleanup Regulation and Ecology's statistical guidance document (Section 1.2).

Two important decisions in developing a soil sampling plan include the sampling approach to be used, and whether or not samples will be collected from only the surface soil or also from depths below the surface. These issues are discussed in Sections A1.1 and A1.2.

A1.1 Sampling approaches

Two basic approaches to soil sampling, **"focused sampling"** and **"area-wide sampling"**, are recognized here. These are descriptive terms adopted here for discussion purposes only, and are not based on regulatory language or used in the technical literature. The focused sampling approach is explained in Section A2.0 and area-wide sampling is explained in Section A3.0. Note that focused sampling can only be used if it can be shown that the method is appropriate for the site (Section A2.0).

Phased sampling

The use of a phased approach to sampling is often desirable during the course of a site investigation. If more than one sampling event is conducted to gather additional information, sample design should be appropriate to meet the objectives of each sampling event. However, the subject of phased sampling is not thoroughly discussed or evaluated in this guidance.

A1.2 Sampling at depth

Subsurface sampling should be conducted unless there is good evidence that any existing soil contamination is confined to the surface soil.[16] As an example, evidence that a hazardous substance was deposited from the air and that it has low mobility in soil could be used as supporting evidence that contamination will only occur at the surface. However, even in this example there may be site-specific reasons (such as regrading or filling of the site) why more information is needed to present a convincing case to Ecology that subsurface sampling is unnecessary.

If subsurface sampling is conducted, note the following:

(i) The point of compliance for cleanup levels based on human exposure via direct contact is fifteen feet below the ground surface,[17] which "represents a reasonable estimate of the depth of soil that could be excavated and distributed at the soil surface as a result of site development activities".

(ii) In some cases, the cleanup of groundwater may require an investigation and cleanup of source contaminants in the soil. The depth of these source contaminants may then determine the maximum soil sampling depth.

Guidance for selecting the maximum sampling depth depends on the sampling approach used. If focused sampling is conducted, see Section A2.1; for area-wide sampling, see Section A3.2.

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[16] The issue of defining "surface" soil is discussed in Section A3.3.1.

[17] WAC 173-340-740(6)(c)

Table 1

Summary of Soil Sampling and Data Analysis Procedures

Sampling method	Depth	Special conditions	When conducted	Compliance analysis	Section
Focused (biased)	Surface/ subsurface	Requires reliable information on location of suspect areas.	Before cleanup	Direct comparison of data with cleanup levels	A2.2
			After cleanup	Direct comparison of data with cleanup levels If grid sampling is used: statistical analysis	A2.2.2
Area-wide (unbiased)	Surface		Before/after cleanup	Statistical analysis	A3.3.1
	Subsurface	Localized contamination	Before cleanup	Direct comparison of data with cleanup levels	A3.3.2.2
			After cleanup	Statistical analysis	A3.3.2.2
		Dispersed contamination	Before/after cleanup	Cumulative statistical analysis Evaluation for groundwater protection (if appropriate)	A3.3.2.3

A2.0 Focused soil sampling

"Focused sampling" means the selective sampling of areas where potential or suspected soil contamination can reliably be expected to be found if a release of a hazardous substance has occurred. This approach may only be used if there is reliable information that can be used to focus sampling efforts on the appropriate locations.

As an example, an investigation of possible soil contamination from a potential source, such as a storage tank or a pipeline, might focus sampling efforts around the structure, rather than conducting area-wide sampling.[18] This example illustrates that the location of a potential source of contamination can be used to decide where to focus sampling efforts. Other examples include: areas of inexplicably stressed or unusual vegetation; areas with markedly distinct soil consistency; low spots where soil fines tend to accumulate; pipe outfall points; and slab edges, especially where slab staining is evident. In other cases, reliable indicators such as soil discoloration or detected volatile substances using field equipment could also provide the basis for focusing sampling on specific areas. However, **if focused sampling is conducted on this or some other basis, the submitted report must explain how the method used for selecting sampling locations ensured that any existing areas of soil contamination would have been found.**

A2.1 Focused soil sampling at depth

If soil contamination is detected at the surface, sample to a depth where the soil is uncontaminated. Information concerning buried material (e.g., an underground storage structure) should also used to determine the sampling depth. If subsurface contamination is found, sampling should extend to a depth where the soil is uncontaminated. There should be sufficient information from the sampling results to determine both the area and depth of contaminated soil requiring remediation.

Selection of the sampling depth should be carefully considered where regrading or filling of the site has occurred so that contamination - previously surficial and now buried - is not overlooked.

If soil is excavated (e.g., to search for leaks along a pipeline), soil samples must be taken from the excavation sidewalls and floor - not the soil piles, to determine whether cleanup levels are met. Where safety concerns preclude the collection of samples from these locations in the excavation, alternative methods should be used, such as using a backhoe bucket to collect a sample. In this case, care should be used to obtain a representative sample. When reporting the results to Ecology, provide an explanation of how representative samples were obtained.

[18] Note that the *Guidance for Remediation of Petroleum Contaminated Soils* provides detailed instructions for the investigation of soil surrounding leaking underground petroleum storage tanks.

A2.2 Comparing data from focused soil sampling with cleanup levels[19]

The concentrations of all hazardous substances in each soil sample should be compared directly with the cleanup levels. The locations of samples which exceed the cleanup level can then be used to delineate the area(s) of soil contamination requiring cleanup.[20] (The sampling points with exceedances are not the areas requiring cleanup; they are used to map the areas requiring a decision on the need for remediation.) Similarly, if there are subsurface exceedances of the cleanup level, use this information to delineate the depth of soil contamination requiring a decision on the need for remediation.

A2.2.1 Evaluating soil piles

The analyses described in Section A2.2 should be based on data from soil samples collected prior to excavation - not from samples taken from piles of excavated soil. Soil with contaminant concentrations that exceed cleanup levels should be segregated into separate piles from "clean" soil.

Contaminated and "clean" soil piles must not be mixed to dilute the contamination. If it becomes necessary to evaluate a soil pile for compliance with a cleanup level, provide a justification when reporting the results to Ecology. The explanation must indicate that the pile was not made by mixing soil from contaminated and "clean" soil piles to achieve compliance with cleanup levels.

To evaluate a soil pile, collect discrete (not composited) samples from different depths in the pile. Use the statistical approach (Section 1.1) to determine whether the soil meets the cleanup level.

A2.2.2 Sampling an area after remediation

Section A2.2 applies to sampling conducted *before* a cleanup is conducted. When sampling an area after it has been remediated (to confirm that cleanup standards are met), use either of the following approaches:

1) Use a grid to plan the sampling locations or use random sampling (Section A3.1). Then use the statistical procedures described in Section A3.3.1 to determine whether cleanup levels have been attained. These procedures permit some exceedances of the cleanup levels, provided that the three decision criteria listed in Section A3.3.1 are met.

2) Focused soil sampling may also be used, comparing contaminant concentrations directly with cleanup levels. If focused sampling was used to demonstrate the effectiveness of the remedial action, provide an explanation of how the sampling locations were chosen.

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[19] New compliance guidance.

[20] If focused sampling indicates that there is an extensive area of soil contamination, it may be necessary to conduct area-wide sampling next to determine the extent of the contamination.

A3.0 Area-wide soil sampling

"Area-wide sampling" is the preferred approach where the spatial distribution of potential or suspected soil contaminants over the study area is uncertain. Consequently, sampling locations must be distributed over the entire study area in an effort to locate any soil that may require cleanup. Since it is impractical to send the entire soil mass to a laboratory for analysis, inferences about the mean (average) concentration of a hazardous substance in the study area, from a statistical analysis of the sampling data, are used to decide whether the area complies with a cleanup level.

A3.1 Recommended methods for conducting area-wide sampling.

(1) The use of a square grid across the study area to define the locations for soil sampling (a form of *systematic* sampling[21]) is recommended.[22] Some deviations from the sample locations on the grid may be necessary (e.g. if a sampling point on the grid is under a building). An alternative approach is to use *random sampling*. With random sampling, there is a possibility that some parts of the study area may, by chance, be inadequately investigated. However, there are some situations where random sampling may be preferable[23] and the reasons for using that approach should be explained if random sampling is conducted.

The grid sampling method described above is intended to answer questions such as:

- What soil contaminants, if any, are present in the area sampled and at what concentrations?
- Does the area meet the MTCA criteria for compliance with a cleanup level?
- If soil contamination exceeds cleanup levels, what are the boundaries of the contaminated area?

If there are additional objectives for the sampling plan, other data collection efforts may be based on methods different from the grid approach. These efforts should be detailed in the report to Ecology.

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[21] See Figure 1 for examples of systematic and random sampling.

[22] Other methods for using grid designs to define sampling locations are described in the literature (e.g., EPA, 1989; Gilbert, 1987).

U.S. EPA. 1989. Methods for evaluating the attainment of cleanup standards - Volume 1: Soils and Solid Media. EPA 230/02-89-042. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC.

Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold, New York.

[23] To illustrate, random sampling may be preferable to systematic sampling if the soil contamination follows a repeating pattern (e.g., the contamination occurs in evenly spaced trenches) that may not correspond to the grid sampling pattern (EPA, 1989).

U.S. EPA. 1989. Methods for evaluating the attainment of cleanup standards - Volume 1: Soils and Solid Media. EPA 230/02-89-042. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC. (Section 6.5)

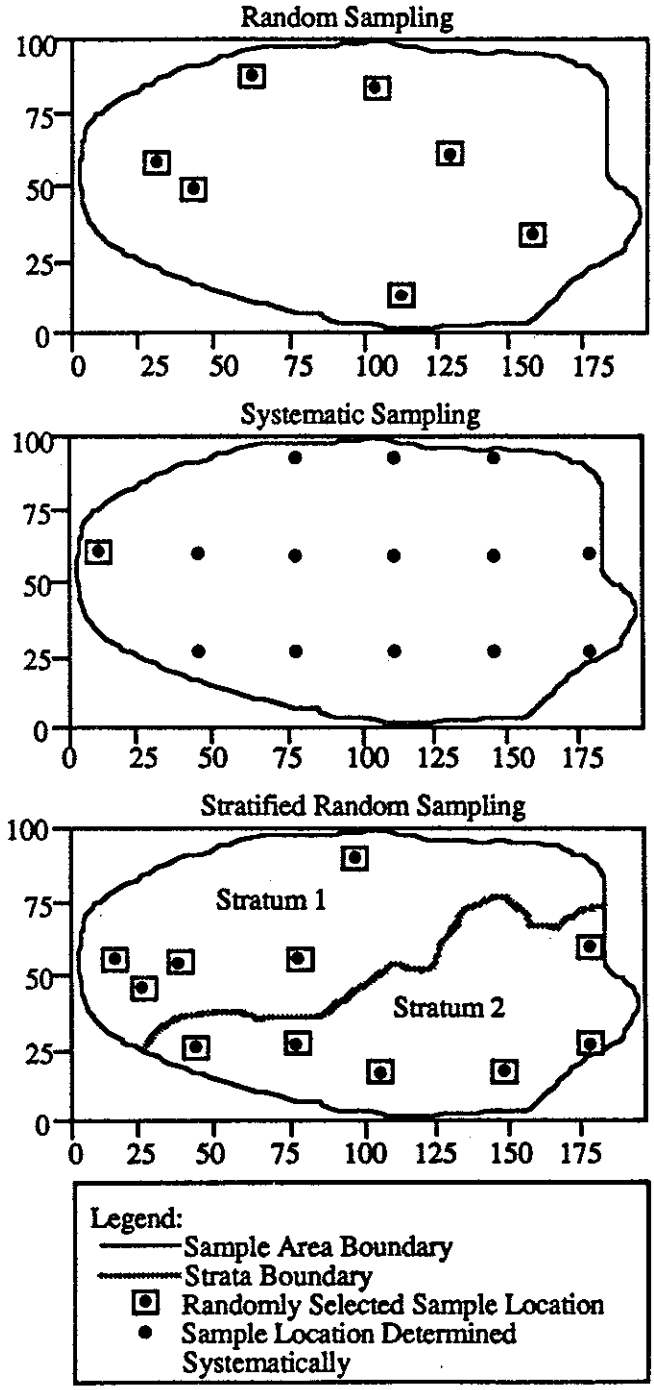

Figure 1a Illustration of random, systematic and stratified sampling (axes are distance in meters)
Source: EPA (1989), see citation in footnote 23

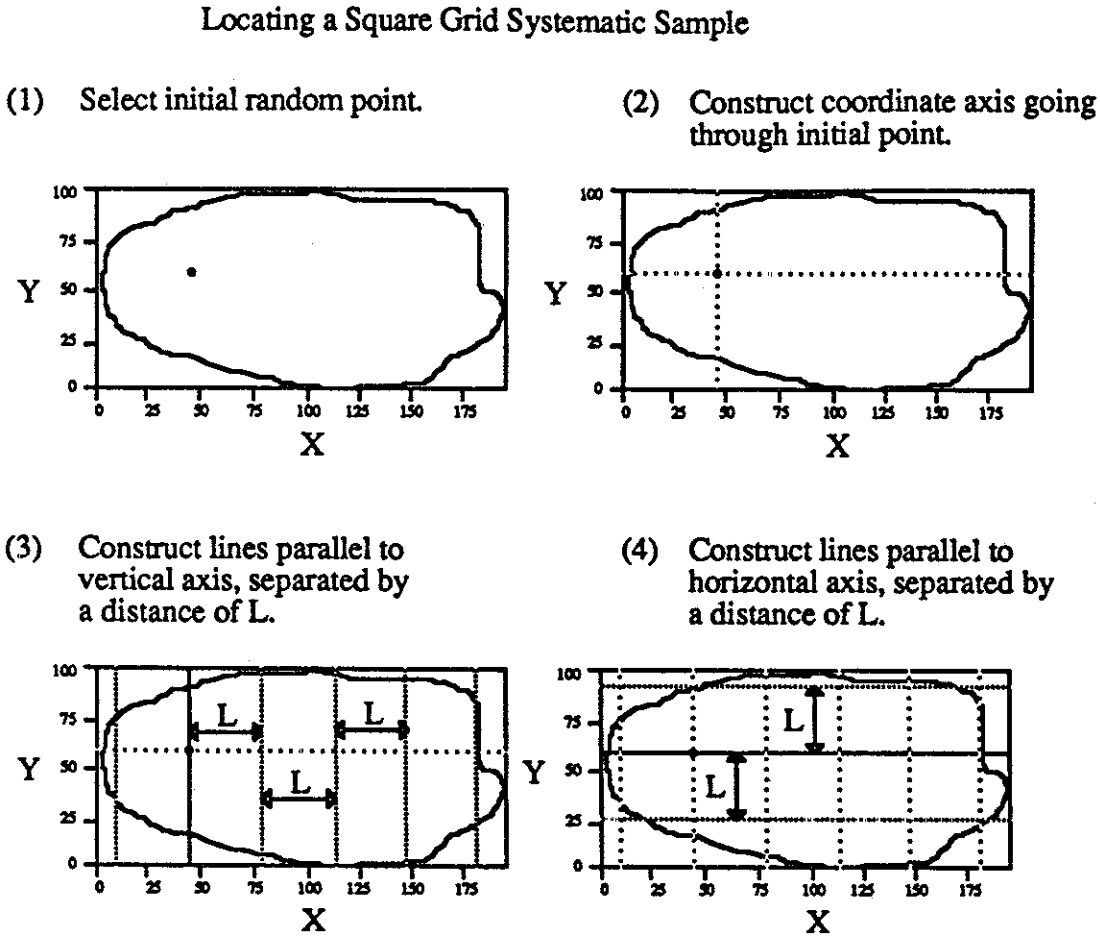

Figure 1b. Procedure for establishing a square sampling grid. Source: EPA (1989), see citation in footnote 23.

(2) Subdivide the study area for the purposes of sampling if there is a logically sound basis for doing so.

Example: An area to be investigated includes a field that may have been contaminated by wind-blown dust, and an adjacent storage area for drums of hazardous chemicals where spills may have occurred. Because of the different histories of the field and storage area, the spatial distribution of soil contamination and the concentrations of hazardous substances in the soil are expected to differ. The field and storage area should therefore be treated as separate study areas.

Different sampling plans could be developed for the field and the storage area, with more intense sampling (i.e., a finer grid spacing) in the storage area, where soil contamination may be patchily distributed in high concentrations.[24] Sampling data from the field and storage area should also be evaluated separately for compliance with cleanup levels.

(3) In some cases, the study area should be subdivided on the basis of exposure units (areas smaller than the study area). In particular, for a residential area it may be necessary to evaluate each lot separately for compliance with cleanup levels.[25]

(4) Grid spacing (i.e. distance between grid nodes[26]) should be based on site-specific considerations. One approach is to consider the expected heterogeneity of the soil contamination and the resolution needed to define the boundaries of a contaminated area. Figure 2 illustrates how a particular grid spacing which may be appropriate for the spatial distribution of soil contamination in one situation may not be suitable in another situation.

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[24] Focused sampling may also be appropriate for the storage area in this example.

[25] For further discussion of the use of exposure units in soil sampling plans, see Neptune, Brantly, Messner and Michael (1990); and Ryti and Neptune (1991).

Neptune, D., Brantly, E., Messner M.J. and Michael, D I. 1990 Quantitative decision making in Superfund. Hazardous Materials Control 3:18-27.

Ryti, R. T. and D. Neptune. 1991. Planning issues for Superfund site remediation. Hazardous Material Control 4:47-73

[26] "Nodes" are the intersections of perpendicular lines on the grid.

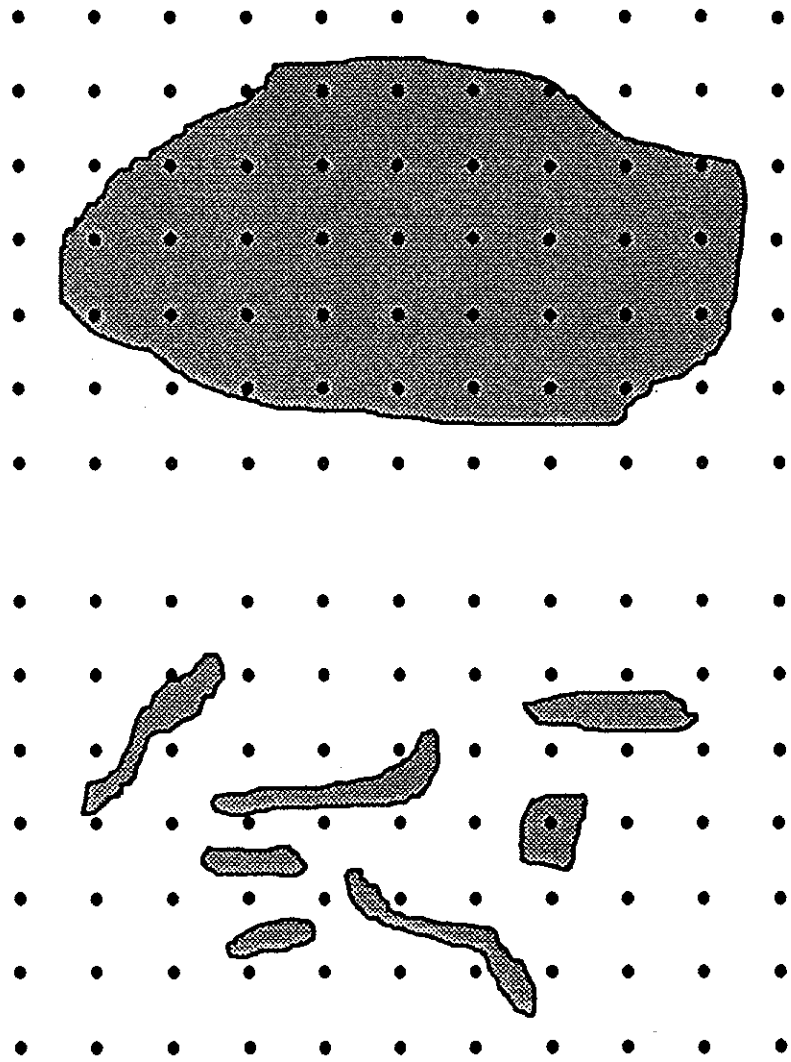

Figure 2. Grid spacing in relationship to the spatial distribution of soil contamination. The grid spacing shown is suitable for the soil contamination in the upper diagram but is too wide for the pattern of soil contamination in the lower diagram.

Another approach is to specify the size of the smallest area of potential soil contamination which should have a high probability of being found. Factors to consider in deciding whether to use this approach include the following:

- Information on past practices (e.g. reports that spills may have occurred).
- Acute toxicity or potential for bioaccumulation of the contaminant(s). Acute toxicity implies that even limited exposure to a small area of contamination may have adverse effects. If the substance bioaccumulates, an untreated area may become a chronic source of tissue contamination in plants or animals living in the area.
- Mobility of the contaminant(s). As an example, substances that are highly soluble in water may be transported by surface runoff from the area to adjacent streams.
- Likely concentration of soil contaminants. For example, a report that a drum containing a pure hazardous chemical may have been spilled indicates the potential of very high concentrations in the soil.
- Exposure potential. This could be high, for example, in an area where children frequently play.
- Lack of suitable field screening techniques, including visual cues (such as staining).

Procedures for designing sampling grids based on the probability of finding a contaminated area of a particular size are described in the literature on "hot spot" sampling.[27] As a rough guide, to have a "high" probability of finding a contaminated area with diameter D or larger, the spacing between grid nodes should be D. (Assumptions: circular area of contamination, square grid and "high" equal to about 80%). For a "very high" (>95%) probability, the grid spacing should be about 0.8D.

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[27] See, for example:

U.S. EPA. 1986. Field Manual for Grid Sampling of PCB (Polychlorinated Biphenyl) Spill Sites to Verify Cleanup. EPA-560/5-86-017. U.S. EPA Office of Toxic Substances, Washington, DC.

U.S. EPA. 1989. Methods for evaluating the attainment of cleanup standards - Volume 1: Soils and Solid Media. EPA 230/02-89-042. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC.

Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold, New York. (Chapter 10)

As an example, to have a very high probability of finding an area 10 feet in diameter or larger, the grid should be designed with an 8 foot spacing between each node.[28]

Compositing as a screening step in intensive area-wide sampling

Compositing is acceptable to Ecology under the following conditions:

- Compositing may be used as a screening tool to search for small areas of contamination. It is not acceptable for use in site characterization.
- Although compositing may be used for making decisions on the need for remediation, it may not be used after remediation to determine whether cleanup standards have been met.
- When reporting compositing data to Ecology, the report must explain the reasons for using compositing and how it was used.
- As noted in Chapter 3 of the *Statistical Guidance for Ecology Site Managers*, compositing is not acceptable for substances such as volatile organics, because it may cause the loss of material from the sample.
- Compositing is not acceptable for contaminants where the practical quantitation limit is near or above cleanup levels.

Because compositing can dilute high concentrations from sampling locations with low concentrations from other locations, a "screening level" concentration must be calculated based on the maximum dilution that could occur:

$$\text{Screening level} = \frac{C}{N}$$

where

C = cleanup level

N = number of samples combined into each composite sample

Example: Intensive grid sampling is conducted for areas with a contaminant concentration of 100 mg/kg or more (C = 100 mg/kg).

[28] Source: Gilbert (1987, Fig. 10.3) Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring Van Nostrand Reinhold, New York

Taking (as an example) 5 samples at a time (N = 5), an equal volume from each is well mixed to form a composite sample (Figure 3). A portion of each of the 5 samples is also retained for possible analysis (subsample set 1 in Figure 3; the composite sample is formed by combining subsample set 2).

The decision criterion is a concentration of 20 mg/kg in the composite sample (100 mg/kg ÷ 5). When the composite sample concentration is less than 20 mg/kg the 5 contributing samples are all below 100 mg/kg and need not be analyzed individually. If the composite sample concentration is 20 mg/kg, one of the contributing samples *may* have a concentration of 100 mg/kg, but this cannot be determined until each sample is analyzed individually.

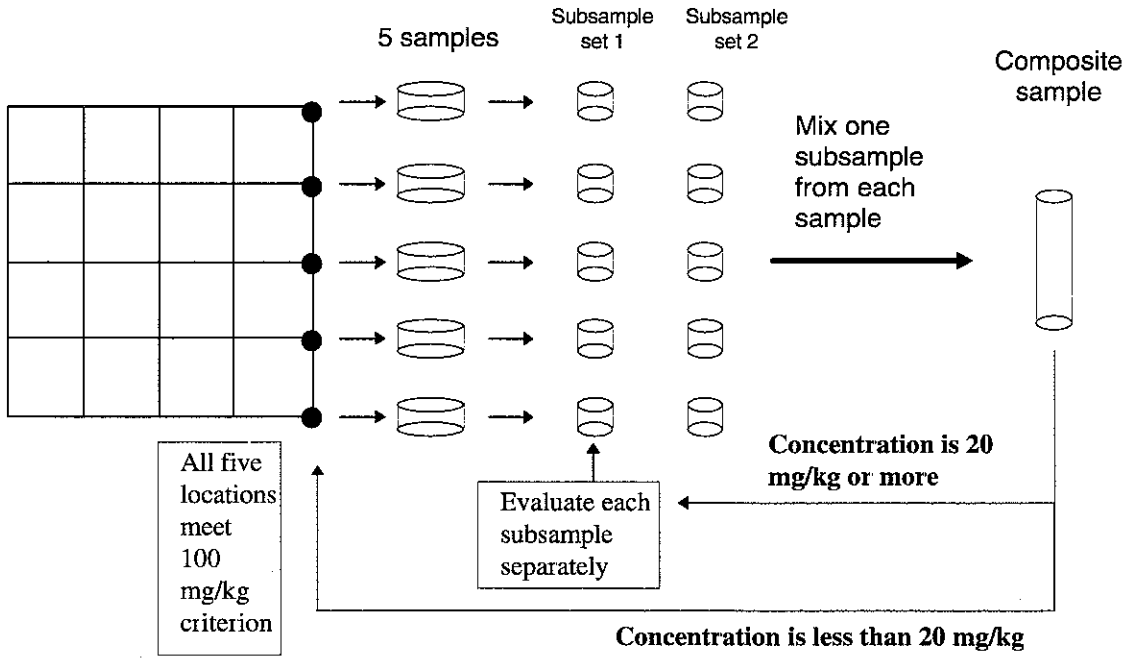

Figure 3. Five adjacent sampling points on the grid are screened for a contaminant concentration of 100 mg/kg, using 20 mg/kg as the screening criterion for the composite sample.

(5) Number of samples. There is no requirement for the number of samples to be analyzed (except in the case of natural and area background). The sample size will be determined by the grid dimensions and spacing between nodes. However, because the upper confidence limit on the mean increases as the number of samples decreases, it will be more difficult to demonstrate that a "clean" area is in fact below a cleanup level with a small number of samples. As a rough guide, it is suggested that at least 10-20 sample locations for each contaminant be analyzed to reduce the chances of failing to demonstrate compliance with a cleanup level for an area that is actually clean.

A3.2 Area-wide soil sampling at depth

See also Section A1.2 for additional information.

Decisions on whether to conduct subsurface sampling and the selection of sampling depths should be based on a conceptual model of the site. In particular, evaluate the possible sources of contamination (e.g., airborne, spills, buried wastes) and how they are likely to affect the distribution of contaminants. Use the conceptual model to justify the selected depths and depth increments, considering also the mobility of the hazardous substances in the soil. The selected depth increments should be consistent with likely options for remediation and with exposure scenarios (e.g., through excavation). For example, 6 inch increments would not be appropriate if the equipment to be used in a remedial action will remove the soil in increments of 2 feet. (The selection of a sampling depth for surface soil is an exception. This depth should be based on exposure considerations - see the definition of surface soil in Section A3.3.1 for guidance.)

After the sampling has been conducted, use the results to reevaluate the assumptions underlying the sampling plan, if possible. For example, if contaminant concentrations are expected to decline with depth but actually increase, there may be buried wastes that were not considered in the conceptual model and sampling may be needed at greater depths than was originally planned.

A3.3 Comparing data from area-wide sampling with cleanup levels

Separate guidance is provided below for surface (Section A3.3.1) and subsurface (Section A3.3.2) soil. For subsurface soil, there are different procedures for evaluating "localized" contamination (Section A3.3.2.2) that is found in area-wide sampling and "dispersed" contamination (Section A3.3.2.3). These terms are defined in Section A3.3.2.1.

Soil piles.

Procedures for evaluating soil piles with focused soil sampling (Section A2.2.1) also apply to area-wide sampling:

The analyses described below for surface and subsurface soils should be based on data from soil ground samples, not from samples taken from piles of the excavated soil. Soil with contaminant concentrations that exceed cleanup levels should be segregated into piles separate from "clean" soil. Contaminated and "clean" soil piles must not be mixed to dilute the contamination. If it becomes necessary to evaluate a soil pile for compliance with a cleanup level, provide a justification when reporting the results to Ecology. The explanation must indicate that the pile was not made by mixing soil from contaminated and "clean" soil piles to achieve compliance with cleanup levels.

To evaluate a soil pile, collect discrete (not composited) samples from different depths in the pile. Use the statistical approach (Section 1.1) to determine whether the soil meets the cleanup level.

A3.3.1 Surface soil

The decision on whether an area complies with a cleanup level is based on three criteria (see Section 1.1):

1. The upper 95% confidence limit on the true population mean, calculated from the sampling data, cannot exceed the cleanup level;

2. No sample concentration can exceed twice the cleanup level; and

3. Less than 10% of the samples can exceed the cleanup level.[29]

Definition. A decision on what depth range constitutes "**surface**" soil should be based on a consideration of the potential for direct exposure, and the chemical and physical properties of potential contaminants. Thus the compliance evaluation should be applied to *unexcavated surface soil which one can directly contact*. However, sampling for volatile contaminants should not be done directly at the soil surface since natural processes could have caused surface concentrations to be diminished. **It is expected that a report to Ecology will explain the depth range selected to represent surface soil, provide a justification for the selection, and a description of the methods used to sample the surface soil.**

A3.3.2 Subsurface soil

For the purpose of establishing compliance with cleanup levels based on risks from direct contact, soil is *evaluated* to a depth of 15 feet, although *sampling* to this depth is not necessarily required (see Section A3.2 and Example 1, below).

Where shallow soil meets bedrock at less than 15 feet, the evaluation can be limited to the actual soil depth. Ecology may require an evaluation of soil at depths greater than 15 feet where there are site-specific reasons why deeper soil contamination may become a threat to human health or the environment. Examples: the site is in an area where soil is typically excavated to depths greater than 15 feet for building foundations; the site has potential for future use as a gravel pit; the site is on a steep slope where future earth movement may expose deep soil; deeper contaminated soils are a known or potential source of continued groundwater contamination, etc.

[29] Adjustments to the second and third criteria may be permitted when cleanup levels are based on background. See Section 4.3.5 of the *Statistical Guidance for Ecology Site Managers* for more information.

A3.3.2.1 Spatial distribution of soil contamination

Separate guidance is given below for "localized" and "dispersed" subsurface soil contamination. These are defined as follows:

Localized subsurface soil contamination occupies a discrete volume and has relatively well-defined boundaries. Possible examples include: a trench or pit used for disposal of wastes and later covered over; soil contaminated by leakage along a pipeline; soil contaminated by a leak from an underground storage facility.[30] Small pockets of soil contamination are not included here and should be treated as "dispersed" subsurface soil contamination.

Although there may not be sufficient data from the soil sampling alone to demonstrate that the contamination is localized, other available information could be considered. For example, historical information on past waste disposal practices may support the interpretation of data from a subsurface soil investigation which show the location of a buried trench. The nature of the contaminants found at a specific location and their concentrations may also provide supporting evidence for localized sampling, particularly if the data are consistent with independent historical information.

Dispersed subsurface soil contamination includes a variety of situations. They range from an even dispersal of a hazardous substance throughout the subsurface soil to clumping of the substance in a patchy distribution (Figure 4).

If it is not clearly apparent that the contaminant has a localized distribution, use the analysis procedures for dispersed contamination.

[30] Although focused sampling can be used for investigating localized soil contamination, there are various reasons why it might be necessary to use area-wide sampling. For example, although historical information may suggest that a trench was formerly used for waste disposal, focused sampling could not be used unless the likely location of the trench was known.

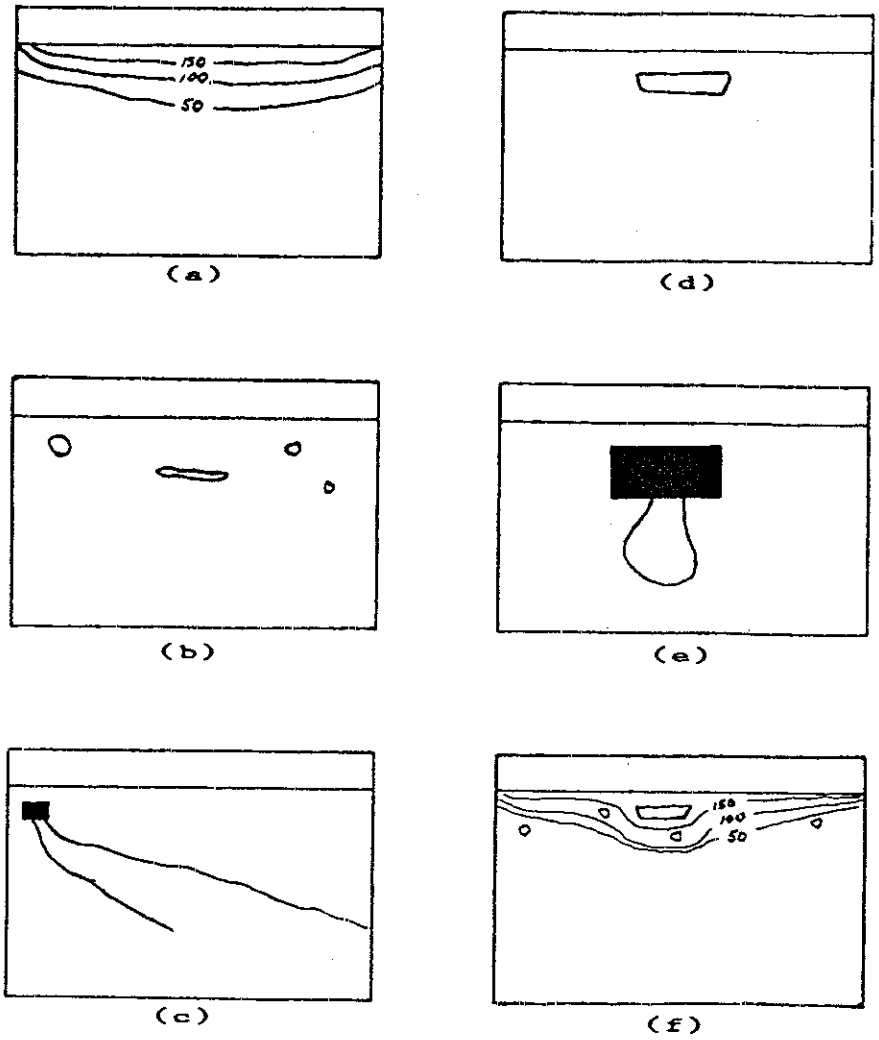

Figure 4 Examples of dispersed and localized contamination

Dispersed

(a) Even distribution Numbers indicate concentration of a hazardous substance at different depths.
(b) Dispersed pockets of contaminated soil
(c) Extensive plume from a leaking storage tank (solid rectangle). The plume does not have well-defined boundaries and is too large to treat as localized contamination.

Localized

(d) Buried trench with well-defined boundaries
(e) Small, well-defined plume from a leaking storage tank (solid rectangle)

Combination

(f) Site with a buried trench (localized contamination) surrounded by dispersed contamination, which includes some pockets of contaminated soil. Unlike the pockets, the trench is considered to be an area of localized contamination, based on its larger size and well-defined boundaries

A3.3.2.2 Analysis for localized contamination

Compliance with cleanup levels is determined by the same approach used for focused soil sampling (Section A2.2). Data for localized contamination should be used to map the boundaries of subsurface soil which exceeds cleanup levels. If the data are insufficient, additional samples from new locations and depths should be collected so the volume of subsurface soil where cleanup levels are exceeded can be defined.

As an example, data from area-wide sampling at different depths might include one sample believed to have come from a buried trench formerly used for waste disposal. Sampling from adjacent locations and depths would then be conducted to map the length, width, top and bottom of the trench.

When sampling an area after it has been remediated (to confirm that cleanup standards have been met), a grid to plan the sampling locations or random sampling (Section A3.1) should be used. Apply the statistical procedures described in Section A3.3.1 to determine whether cleanup levels have been attained. These procedures permit some exceedances of the cleanup levels, provided that the three decision criteria listed in Section A3.3.1 are met.

A3.3.2.3 Analysis for dispersed contamination

See also Section A3.2 for additional guidance.

Use the cumulative analysis procedure described below. This procedure is based on the exposure assumption of direct contact with subsurface soils mixed with overlying soil layers during excavation and then brought to the surface.[31] The procedure applies only to health-based cleanup levels, which can be found in the *MTCA Cleanup Levels and Risk Calculation (CLARC II) Update* (listed in Section 1.2 of this guidance). In using these procedures, Ecology may deem it appropriate to use sampling data from less than the entire study area.

Ecology may approve the use of another procedure based on site-specific considerations. If another procedure is used, an explanation of how the analysis was conducted, the reasons for using it, and site-specific reasons why the cumulative analysis procedure was not used is necessary.

[31] The conceptual model of mixing does not imply an endorsement of mixing clean and contaminated soils as a method of achieving cleanup levels at a site.

In addition to the cumulative analysis procedure, there are other analyses for subsurface soil sampling data which may be required on a site-specific basis (see Sections A3.3.2.4 and A3.3.2.5). They include, for example, an analysis to address protection of groundwater from subsurface soil contamination, an issue which is not covered in the cumulative analysis procedure.

Cumulative analysis procedure (direct contact pathway):[32]

Using the statistical approach, analyze the subsurface soil data in steps, adding data from the next depth at each step. The three decision criteria used in the statistical approach (described in the surface soil discussion) are applied at each step as follows:

(i) After evaluating the surface soil data, combine the data from the first depth increment with the surface-level data. Apply the three decision criteria to the combined data to evaluate the soil from the surface through the first depth increment.

Note that evaluation of the surface-level soil is conducted separately from the evaluation of soil from the surface through the first depth increment. If the surface-level soil data fail one (or more) of the three decision criteria, this "fail" evaluation is not changed by a "pass" evaluation of the soil from the surface through the first depth increment. A fail decision at any of the cumulative depth increments indicates that soil cleanup options and the selected remedial action (including no action) need to be evaluated and supported as adequate and effective. Also note that if the remedial decision is to cap the contaminated subsurface soil with clean soil (i.e., rely solely on containment), *expected concentrations from the clean soil cannot be used to "dilute" data from the underlying soil.*

(ii) Combine the data from the second depth increment with data from the first depth increment and the surface. Apply the three decision criteria to the combined data to evaluate the soil from the surface through the second depth increment.

(iii) Repeat this procedure for the each successive depth increment.

[32] New compliance guidance.

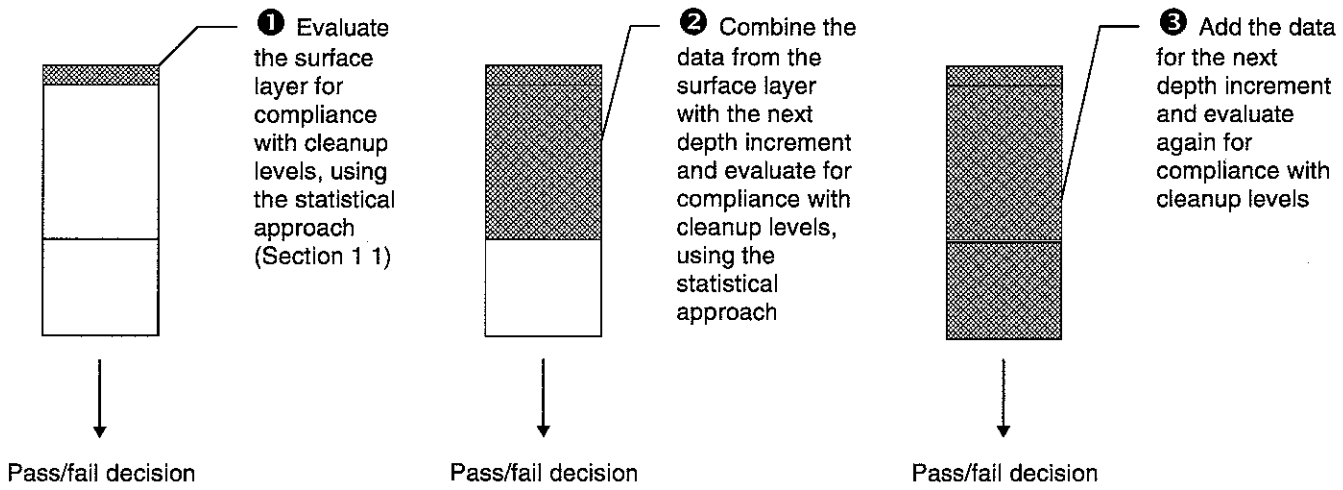

Figure 5. Cumulative analysis procedure for evaluating subsurface soil layers for compliance with cleanup levels.

Two examples are provided below.

Example 1. An area used for the storage and shipping of a hazardous substance is investigated because of concerns that past handling practices have contaminated the soil. The substance was spilled onto the ground in various places and dispersed by the wind so that contamination is expected over the area.

Area-wide soil sampling was conducted at the surface and at depths of 1 foot and 2 feet. Based on site-specific considerations, the 0-0.5 foot layer is considered to be directly contactable surface soil. No samples were collected at depths greater than 2 feet. The site history indicates that the hazardous substance was deposited at the surface which is consistent with the concentration depth gradient. Concentrations of the deeper soil samples are low relative to the cleanup level of 15 ppm. For these reasons, it was decided not to continue sampling to greater depths.

Results from soil sampling of the area are shown in Table 2. For the purposes of illustrating the cumulative analysis procedure, the number of samples has been kept small. The example should not be used as guidance on the number of samples to collect. Similarly, the depth increments used in these examples are not intended to serve as recommendations for use in the design of sampling plans.

Table 2

Soil Sampling Data for Example 1

Depth (feet)	Concentration (ppm)				
0-0.5	9.7	10.1	14.7	15.3	10.0
	6.9	7.7	8.9	7.7	6.6
1	3.9	5.2	9.6	7.8	5.1
2	2.2	2.5	3.4	3.0	2.3

Analysis: The cleanup level in this example is 15 ppm. Data from 1 and 2 foot depths were combined for the compliance analysis. If the increment had been greater (e.g., 1 and 5 foot), the data should have been analyzed separately.

Results of the cumulative analysis are summarized in Table 3. For the surface soil (0-0.5 foot), the upper 95% confidence limit (based on a lognormal distribution) is 11.8 ppm, which is less than the cleanup level of 15 ppm. However, 1 of the 10 samples exceeds 15 ppm, and this does not meet the criterion that less than 10% of the samples exceed the cleanup level. For this reason, a "fail" decision applies to the surface soil.

For the deeper soil (1-2 foot), *the data from these samples are combined with the surface soil data*. The upper 95% confidence limit (based on a lognormal distribution) for the 20 samples is 9.7, which is less than the cleanup level. Less than 10% of the samples exceed the cleanup level and no single sample exceeds twice the cleanup level. Since all three criteria for compliance with the cleanup level are met, a "pass" decision applies to the soil volume from 0 to 2 feet, although the "fail" decision for the surface soil still stands.

Table 3

Cumulative Analysis of Soil Sampling Data in Table 2

Depth (feet)	No. of samples	Upper 95% confidence limit	Distribution	Less than 10% of samples exceed cleanup level?	No single sample exceeds twice cleanup level?	Decision
0 - 0.5	10	11.8	Lognormal	No	Yes	***Fail***
0 - 2	20	9.7	Lognormal	Yes	Yes	***Pass***

Cleanup level in this example is 15 ppm.

Although the *analysis* in this example only included data to a depth of 2 feet, the *evaluation* that subsurface soil complies with cleanup levels applies to a depth of 15 feet (see Section A3.3.2), because the evidence indicates that deeper soil does not exceed cleanup levels. *Ecology's acceptance of this evaluation would depend also on acceptance of the reasons given earlier in this example for limiting sampling to a depth of 2 feet.*

Example 2. An investigation is conducted of an area where construction debris and a variety of other materials had been used to fill in a large low-lying area to a depth of about 20 feet. Some of the materials are contaminated with a hazardous substance in varying concentrations.

Concentrations of the substance found in area-wide soil sampling at the surface (in this example, defined as 0-0.5 foot) and at depths down to 15 feet are shown in Table 4.

Table 4

Soil Sampling Data for Example 2

Depth (feet)	Concentration (ppm)									
0 - 0.5	0.87	1.04	0.92	1.19	0.81	0.92	0.79	1.15	0.89	0.95
0.51 - 5.0	1.39	1.56	1.51	1.38	1.49	1.91	1.71	1.24	1.40	1.49
5.1 - 10.0	2.03	2.08	2.12	1.90	2.10	1.59	1.94	1.86	2.22	1.93
10.1 - 15.0	5.50	4.87	4.13	6.50	3.77	4.18	4.50	4.59	4.75	4.59

Analysis: The cleanup level is 5 ppm. As in the previous example, the surface soil (0-0.5 foot in this example) is evaluated first. Then the soil is evaluated to progressively greater depths, using 5 foot increments. Results are summarized in Table 5.

Table 5

Cumulative Analysis of Soil Sampling Data in Table 4

Depth (feet)	No. of samples	Upper 95% confidence limit	Distribution	Less than 10% of samples exceed cleanup level?	No single sample exceeds twice cleanup level?	Decision
0-0.5	10	1.04	Lognormal	Yes	Yes	***Pass***
0-5	20	1.38	Lognormal	Yes	Yes	***Pass***
0-10	30	1.66	Lognormal	Yes	Yes	***Pass***
0-15	40	2.76	Lognormal	Yes	Yes	***Pass***

Cleanup level in this example is 5 ppm.

Note on statistical calculations: For the 0-10 foot evaluation, the lognormal assumption is based on the probability plot analysis in MTCA*Stat*. A normal distribution could also have been assumed, since the W test procedure in MTCA*Stat* rejected lognormal but not normal. Under the normal assumption, the upper 95% confidence limit is 1.62.

For the 0-15 foot evaluation, the lognormal assumption is based on the probability plot analysis in MTCA*Stat*. However, the W test procedure in MTCA*Stat* rejected both normal and lognormal distributions. The option to accept the results of the probability plot analysis was chosen.

A3.3.2.4 Other analyses: Protection of groundwater from soil contamination

The preceding cumulative analysis procedure cannot be used to determine whether subsurface soil contaminant concentrations are protective of groundwater. The cumulative analysis procedure is based on the exposure assumption of direct contact with soil that has been excavated to the surface. It does not include an analysis of the effect of contaminated subsurface soil on contaminant concentrations in groundwater.

The Model Toxics Control Act (MTCA) currently has three procedures for generating soil cleanup levels that are protective of groundwater: the Method A Table and two procedures under Method B. The simplest and quickest way to obtain soil cleanup levels that are protective of groundwater is to look them up in the Method A Table [WAC 173-340-740(2)]. However, the table contains a limited number of compounds and may not be sufficient for sites with a wide variety of hazardous constituents.

Soil cleanup levels that are protective of groundwater can also be derived using two procedures under MTCA Method B [WAC 173-340-740(3)]. In the first, soil cleanup levels are calculated by multiplying the groundwater cleanup level [WAC 173-340-720] by 100. Method B groundwater cleanup levels can be found in the *MTCA Cleanup Levels and Risk Calculation (CLARC II) Update* (listed in Section 1.2 of this guidance). In the second, a "site-specific" demonstration is allowed. This demonstration typically includes the use of models and leaching tests to verify that soil cleanup levels are protective of groundwater.

The Department of Ecology is currently preparing guidance that will better define what should be done when deriving soil cleanup levels that are protective of groundwater. This guidance has been targeted for publication in 1995. Several issues and subjects are currently being researched for the guidance: the use of laboratory leaching tests and models, empirical relationships (if any) between soil and groundwater contaminant concentration, and the use of receptor-based groundwater contaminant concentrations to derive soil cleanup levels at a source area. The guidance will also contain a process on how to use soil cleanup levels that are protective of groundwater. Method A or Method B procedures can be used to determine soil cleanup levels protective of groundwater until the guidance becomes available.

A3.3.2.5 Other analyses: Selection of remedy

In addition to the cumulative analysis calculations illustrated in Examples 1 and 2, which are based on the assumption that soil will be excavated to a depth of 15 feet, other remedial actions may be developed that require alternative calculations. The evaluation of alternative remedial actions should include these calculations. Examples 3 and 4 show how the calculations could be adapted to evaluate specific remedial actions.

Example 3. The cumulative analysis procedure may produce a "fail" decision for relatively uncontaminated deeper soil because of high concentrations of a hazardous substance in the overlying soil. From an exposure perspective, removal of the deeper soil, together with the overlying contaminated soil, would produce an unacceptable level of contamination in the excavated mixture. However, this problem could be addressed by limiting remediation to the overlying contaminated soil, rather than including the uncontaminated deeper soil as well.

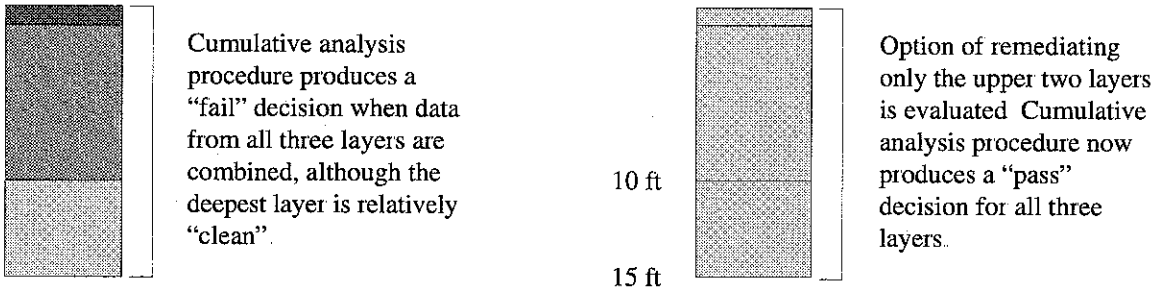

Figure 6. Evaluation of remedial alternative in Example 3

Example 4. An important point is that if this site were expected to be excavated to a depth of 10 feet as part of a site redevelopment proposal, it would be more appropriate to evaluate the 10-15 feet deep data for compliance without combining it with data from the overlying layers.

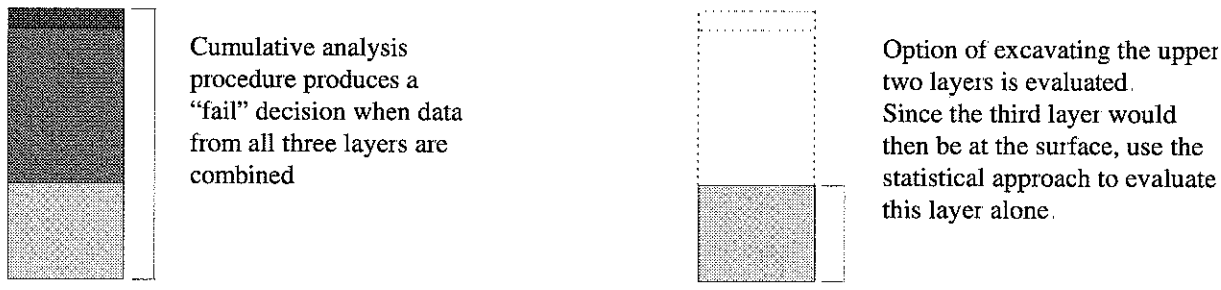

Figure 7. Illustration of how the soil data should be reanalyzed to evaluate a remedial alternative of excavating contaminated soil.

A3.3.2.6 Combined approaches

At some sites, there may be both dispersed and localized subsurface soil contamination. Use the appropriate evaluation procedure for each case. Do not include localized contamination sampling data in the evaluation of dispersed contamination.

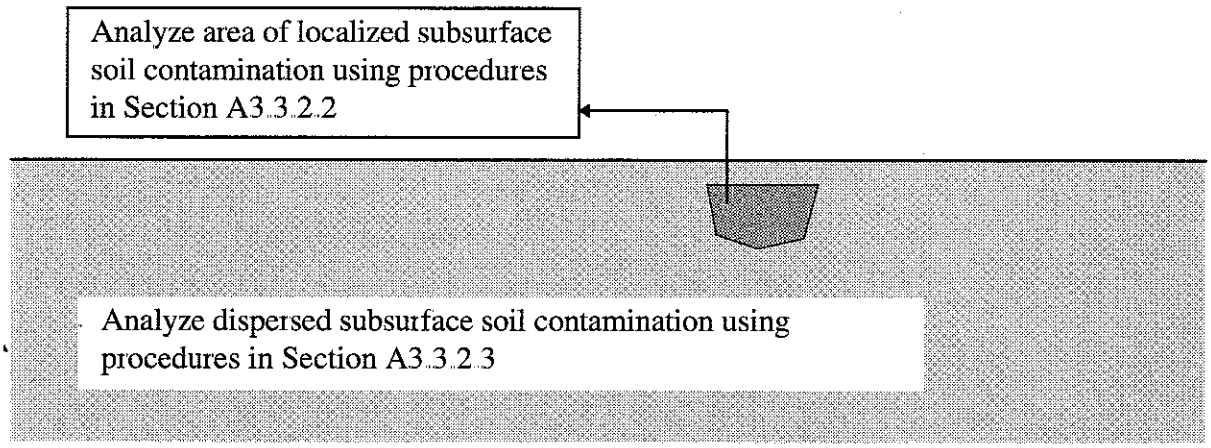

Figure 8. Example of combined approach for subsurface soil with localized and dispersed contamination.

A4.0 GROUNDWATER MONITORING

This guidance does not supersede or replace monitoring requirements of other applicable or relevant and appropriate regulations, but is in addition to those regulations.

Caution on applicability of this guidance. Many issues regarding the sampling of groundwater and data analysis typically involve site-specific considerations that cannot be anticipated in written guidance. For sites where the agency has formal involvement, Ecology site managers may provide site-specific direction that need not necessarily conform to this guidance. However, for independent remedial actions that are conducted without Ecology oversight, the guidance provided here is intended to increase the likelihood that the cleanup and Independent Remediation Report will be approved by Ecology.

Limitations of the guidance. Because the design of groundwater sampling plans is a complex issue that typically depends on many site-specific considerations, detailed recommendations are not provided here. However, the following guidance covers some of the important issues. *Note that the guidance is not intended to serve as an exhaustive review of all the technical and regulatory issues that should be addressed in the investigation and cleanup of groundwater.*

Organization of this groundwater monitoring guidance section.

Report preparation (A4.1, p. 39)	Provides guidance for preparing a report to Ecology on issues relating to groundwater sampling.
Remedial investigation (A5.0, p. 41)	Provides guidance on monitoring groundwater before making a decision on whether remediation is required.
Sampling following remediation (A6.0, p. 46)	Provides guidance on compliance monitoring to be conducted after a remedial action has been implemented.
Alternate sampling proposals (A7.0, p. 51)	Discusses expectations if alternate performance or confirmational monitoring plans are proposed to Ecology.
Area background (A8.0, p. 51)	Provides comments to consider if groundwater contamination is proposed to be at or below area background.
Off-site source (A9.0, p. 52)	Describes the required information to support a proposal that groundwater contamination is due to an off-site source.

A4.1 Issues to consider in preparing a report for submittal to Ecology.

This section is primarily intended to provide assistance in preparing an Independent Remediation Report by explaining Ecology's expectations concerning those parts of the Report that deal with groundwater. This section may be used to review the Report for completeness before submission to Ecology and after by Ecology reviewers. It may also be helpful in preparing reports for Ecology for sites where the agency has formal involvement.

(1) **Soil contamination was found but no hydrogeological investigation was conducted.**

Does the Report provide a satisfactory explanation for concluding that a hydrogeological investigation was not justified? The explanation should cite pertinent information including: a) depth to groundwater; b) vertical separation between soil contaminants and the first aquifer; c) soil type (sand, gravel, silt, clay); d) amount of rainfall or precipitation; and e) mobility of contaminants.

A cross-sectional view should also be provided showing the maximum depth of the soil contamination. The view should also include: a) contaminant type and changes in concentration with depth; b) soil types; and c) groundwater elevation or depth below ground surface.

Ecology expects that a hydrogeological investigation will be conducted at any site where (1) soil contamination is found within 10 feet of the groundwater table and there is permeable soil, or (2) when a soil contaminant is potentially mobile considering the site's geological setting, particularly if there is a high concentration of contamination relative to the groundwater standard and the contamination is not recent to the site.

(2) **A hydrogeological investigation was conducted and the report concludes that the groundwater complies with cleanup levels.**

Was the number of wells installed, their location and the screening depths appropriate for the investigation, based on the available hydrogeological information?

Was sampling conducted at locations in the groundwater where contamination was most likely to be found if a release to groundwater has occurred?

If there is a concern that groundwater may have been contaminated with substances that are immiscible in water, was sampling and analysis conducted appropriately to detect the substances?

Does the sampling and analysis comply with guidance in Section A5.0?

(3) **A groundwater investigation was conducted and the report concludes that the groundwater contamination exists above cleanup levels.**

See comments under Section A4.1 (2)

Has sufficient sampling been conducted to define the maximum extent of contamination?

Does the sampling and analysis conducted **prior** to remediation comply with guidance in Section A5.0? Does the sampling and analysis conducted **after** remediation comply with guidance in Section A6.0?

Table 7

Summary of Groundwater Monitoring and Data Analysis Procedures for Use in Making a Cleanup Decision (remedial investigation)

Remedial investigation stage	Minimum number of samples per well	Pass criteria for all wells	Comments	Section
Stage 1 (screening level)	2 samples/well, 3-6 months apart, covering seasonal fluctuations	Concentrations below MDL or natural background *and* No other evidence for release to groundwater* *and* Approval from Ecology	No further action if all criteria met	A5.2
Stage 2 (screening level)	4 samples/well, including previous 2 from Stage 1 (if applicable), collected quarterly	Concentrations below cleanup level *and* Approval from Ecology	No further action if both criteria met	A5.3
Screening level tests not met	More than 4 samples/well, collected quarterly	Statistical analysis criteria	Must be continued until cleanup standards are met	A5.4

* If this criterion is not met, begin at Stage 2

A5.0 Groundwater monitoring for a remedial investigation.

The following procedures apply to the investigation of groundwater before making a decision on whether remediation is required (see Table 7). The objective of these procedures is to determine whether groundwater cleanup levels are met. However, a hydrogeological investigation will have additional objectives (e.g., to establish the direction of groundwater flow) that are not addressed here. Sampling plans and data analysis methods to meet those objectives must be established on a site specific basis.

A5.1 Stage 1 and Stage 2 screening level procedures.

Normally several years (or more) of groundwater monitoring will be needed before there are enough data to establish statistically whether cleanup levels are met (see Section 5.3 in the *Statistical Guidance for Ecology Site Managers*). To expedite decisions in exceptional cases, two screening-level procedures (Stage 1 and Stage 2) are provided below for requesting a determination from Ecology, based on results from sampling over a year or less, that groundwater is not contaminated at levels requiring remediation.

Note that the Stage 1 and 2 procedures are provided only to reduce the duration of sampling required before a decision can be made. **They do not provide for any reduction in the thoroughness of the groundwater investigation (e.g., fewer monitoring wells or sampling points).**

Independent remedial actions. If groundwater monitoring is terminated at Stage 1 or 2, provide an explanation in the Independent Remedial Action Report. This includes an explanation as to how the Stage 1 or 2 criteria for requesting a decision from Ecology are met. If Ecology determines that site-specific information does not support the termination of monitoring at either Stage 1 or 2, the monitoring must be resumed until it can be demonstrated that cleanup levels are met, using the statistical criteria described in Section 1.1 of this guidance. (See also Section 5.3 in the *Statistical Guidance for Ecology Site Managers*.)

Stage 1 monitoring (Section A5.2) is intended to provide a means for establishing that groundwater contamination is not a concern with only a limited amount of sampling.

Stage 2 monitoring (Section A5.3) can be conducted if the Stage 1 monitoring criteria are not met. Here there is a second opportunity to demonstrate, from a limited amount of sampling, that groundwater is not contaminated at levels requiring remediation.

If the Stage 2 criteria are not met, you may choose either to proceed with plans for remediation or continue with groundwater sampling. If sampling continues, the data must be analyzed using the prescribed statistical criteria to demonstrate compliance with cleanup levels (Section A5.4).

A5.1.1 Conditions for relying on Stage 1 and Stage 2 monitoring

The criteria for terminating monitoring at Stage 1 or Stage 2 include approval from Ecology. In making a decision, Ecology will consider not only the groundwater monitoring results, but the level of confidence regarding interpretations of site conditions. The level of confidence evaluation is a judgment of the probability of a false negative decision (low uncertainty regarding the exceedance of standards) based on available information. Some of the issues that are considered in the evaluation include the following:

- The remedial investigation must provide an adequate understanding of the groundwater system to evaluate potential contaminant pathways, including the source of contamination, direction of groundwater flow, etc.
- Contaminants must be adequately characterized. There must be an acceptable description of the selection of contaminants and an explanation why they are appropriate and sufficient for the investigation.
- Sampling points must be placed where they are most likely to find potential contamination.
- Quality assurance and quality control procedures must be acceptable. (e.g., the sampling protocols used must be satisfactory).
- Terminating monitoring at Stage 1 or 2 is not appropriate if there is the potential for future contamination (e.g., if soil contamination may contaminate the groundwater in the future).
- Terminating monitoring at Stage 1 or 2 is not appropriate if there is evidence for a trend of increasing contaminant concentrations in the groundwater over time.

This list does not preclude the possibility that Ecology may deny a request to terminate monitoring at Stage 1 or Stage 2 based on other information or considerations. Ecology may also require the expansion of monitoring to other locations, modification of monitoring (e.g., in analytical approach), or other steps taken to decrease uncertainties.

A5.2 Remedial investigation - Stage 1 monitoring[33]

Sampling requirements: Collect two samples from each sampling point. The sampling dates should be 3-6 months apart and must include the wet and dry seasons. Any other influences, such as tidal fluctuations, must also be taken into account to ensure that the samples are representative of high and low water table conditions.

Data analysis: Remediation is not required and no further groundwater monitoring is necessary if all of the following conditions are met:

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[33] New compliance guidance.

(1) None of the contaminants of concern were found *at any of the sampling locations in any of the samples* at concentrations above the method detection limit (or above natural background, in the case of naturally occurring substances); and

(2) There are no other indications that a release to groundwater may have occurred or has a high potential to occur considering the properties and concentrations of contaminants in the soil, geological climatic setting of the site, and trends from existing groundwater data; and

(3) Ecology approves a request to terminate monitoring at Stage 1. The decision is based on a review of the available information (Section A5.1.1). Approval requires an assessment, for example, that the sampling locations in the groundwater would have detected potential contamination, and that the failure to detect contaminants of concern above cleanup levels was not related to seasonal, tidal or other periodic variations in the groundwater level, the direction of groundwater flow or other characteristics.

Application: Stage 1 monitoring is intended to provide a method for identifying sites where Ecology may determine that there is clear and convincing evidence that groundwater has not been contaminated and that the amount of groundwater monitoring normally required to establish compliance with cleanup levels is unnecessary. *Termination of groundwater monitoring at Stage 1 is only expected to be acceptable to Ecology in exceptional cases.* Until a decision is made by Ecology, monitoring wells must be properly maintained and secured so that further sampling can be conducted if required.

If the conditions listed above are not met, follow the procedures described in Section A5.3

A5.3 Remedial investigation - Stage 2 monitoring[34]

Sampling requirements: Collect two additional samples from each well on a quarterly basis. With these samples and the two described under Section A5.2, data from four sampling dates should now be available from each well.

Data analysis: Remediation is not required and no further groundwater monitoring is necessary if all of the following conditions are met:

(1) None of the contaminants of concern were found *at any of the sampling locations in all four of the sampling events* at concentrations above the cleanup levels; and

(2) Ecology approves a request to terminate monitoring at Stage 2. The decision is based on a review of the available information (Section A5.1.1). Approval requires an assessment, for example, that the sampling locations in the groundwater would have detected potential contamination, and that the failure to detect contaminants of concern above cleanup levels was not related to seasonal, tidal or other periodic variations in the groundwater level, the direction of groundwater flow or other characteristics.

Application: These criteria may be used by Ecology to determine that there is sufficient evidence that groundwater contaminants do not exceed cleanup levels and that further groundwater sampling is unnecessary. Until a decision is made by Ecology, monitoring wells must be properly maintained and secured so that further sampling can be conducted, if necessary.

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[34] New compliance guidance.

If the criteria are not met, determine whether groundwater remediation should be conducted, based on the requirements of the MTCA Cleanup Regulation (WAC 173-340-360). If remediation is not conducted, continue monitoring as described in Section A5.4. If groundwater remediation is conducted, compliance monitoring must be conducted following remediation, as described in Section A6.0.

A5.4 Sampling requirements if Stage 1 and 2 criteria are not met.

Sample quarterly from each well. Data from more frequent sampling may be used to evaluate the site, if approved by Ecology.[35] Sampling must continue until cleanup levels are met.

Data analysis: Compliance with cleanup levels must be demonstrated using the statistical data analysis procedures described in items (1) and (2) in Section 1.1. Note that data from different wells cannot be combined because compliance must be demonstrated at each location.[36]

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[35] Increasing the frequency of sampling may produce a high serial correlation between the data, violating the statistical assumption of independence (*Statistical Guidance for Ecology Site Managers*, Section 5.3.5.2). EPA (1992) provides methods for analyzing groundwater data to estimate the effect of increasing the sampling frequency on the serial correlation.

U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater. EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC.

[36] WAC 173-340-720(8)(c)(iv)

Table 8

Summary of Monitoring and Data Analysis Procedures Following Groundwater Remediation

Stage	Decision	Comments	Monitoring required	Analysis	Section
Performance monitoring	Terminate groundwater treatment?		Site-specific	Site-specific	A6.1
	Begin collecting data to determine whether cleanup standards are met?		Site-specific	Site-specific	A6.1.1
	Are cleanup standards met?		At least 3 years, monthly to quarterly*	Statistical analysis for compliance	A6.1.2 A6.1.3
Confirmational monitoring	Long-term compliance with cleanup standards?	Sites where periodic review not required	At least 3 years, monthly to quarterly*	Site-specific	A6.2.2
		Sites where periodic review required	Varies, may be indefinite	Site-specific	A6.2.1

* Data used to determine whether cleanup standards have been attained may also be sufficient to determine whether the attainment can be expected to be long-term. In some cases, the data may not be sufficient and Ecology will require additional monitoring

A6.0 Sampling following groundwater remediation or source control efforts (compliance monitoring)

The MTCA Cleanup Regulation[37] requires that compliance monitoring be conducted following groundwater remediation. Compliance monitoring includes (i) **Protection monitoring**; (ii) **Performance monitoring**; and (iii) **Confirmational monitoring**.

> **Protection monitoring** is conducted to: "Confirm that human health and the environment are adequately protected during construction and the operation and maintenance period of an interim action or cleanup action as described in the safety and health plan".[38] Protection monitoring is not addressed in this guidance.
>
> **Performance monitoring** is addressed in Section A6.1.
>
> **Confirmational monitoring** is addressed in Section A6.2.

A compliance monitoring plan must be prepared before conducting groundwater remediation. Guidance is not provided here on every element of the plan, such as the number and location of monitoring wells, because these typically involve so many site-specific considerations that it is difficult to provide useful generalizations. However, Ecology expects that all compliance monitoring plans will include a discussion of all site-specific decisions, clearly explained goals and objectives, and the rationale for each decision.

As remediation proceeds, it may be necessary to make revisions to the plan (e.g. because proposed methods of data analysis were based on assumptions about the data that prove incorrect). However, it is essential that the initial plan provide a thorough and well thought out starting point for compliance monitoring based on the information available at the time.

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[37] WAC 173-340-410. Note that while the application of compliance monitoring to groundwater cleanup actions is emphasized in this guidance, compliance monitoring is required for all cleanup actions.

[38] WAC 173-340-410(1)(a)

A6.1 Performance monitoring

Performance monitoring is conducted to "confirm that the interim action or cleanup action has attained cleanup standards and, if appropriate, other performance standards."[39] "Other performance standards" should be established as needed to meet site-specific objectives. They could apply, for example, to the use of indicators (e.g., chloride ion concentration, presence of a sheen) to determine whether expectations are being met during remediation or testing. As another example, they may be established to determine whether engineering design specifications connected with the remedial action (e.g., hydraulic conductivity of a barrier) are being met.

The U.S. EPA guidance document, *Methods for Evaluating the Attainment of Cleanup Standards. Volume 2: Groundwater,*[40] identifies three performance monitoring decision points for groundwater remediation. They are illustrated in Figure 6.1 of that document (included here, in part, in Appendix II). This three-step evaluation process is most applicable to active groundwater remediation (e.g., "pump and treat") but can also be adapted to other actions such as contaminant source removal followed by groundwater monitoring. The steps in the evaluation are:

(1) **Deciding when to end treatment.** This is a technical determination that remediation has proceeded to a point where it can be demonstrated that cleanup standards have been attained. A plot of the contaminant concentration data, showing changes over time, provides the simplest approach for making this decision. However, the plot may not always show an unambiguous trend and may be open to different interpretations. The EPA guidance (Chapter 6) shows examples of data plots (e.g. Figures 6.3 and 6.8) and discusses statistical alternatives to visual inspection of the plots, such as regression analysis, which can be helpful in making a decision. In addition, there may be performance standards other than contaminant concentrations that are also important in making the decision. For remedial actions where this is a relevant issue, the compliance monitoring plan must include an explanation of how the decision will be made, the rational for the decision process and the assumptions underlying the approach.

(2) **Deciding when to begin collecting attainment data.** The EPA guidance (Chapter 7) recommends that data used in determining whether cleanup standards have been met should be collected only after the groundwater system has reached steady state: "After terminating treatment and before collecting water samples to assess attainment, a period of time must pass to ensure that any transient effects of treatment on the groundwater system have sufficiently decayed."[41] In this guidance, recommendations regarding the achievement of steady state conditions before collecting data to determine whether cleanup standards have been attained are given below (Section A6.1.1). Guidance on the sampling schedule for collecting the data is provided in Section A6.1.2.

(3) **Deciding whether cleanup standards have been attained.** Although the EPA guidance (Chapters 8-9) provides a variety of methods for demonstrating attainment, the approach that should be used to comply with the MTCA Cleanup Regulation and Ecology guidance is described below in Section A6.1.3.

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39 WAC 173-340-410(1)(b)

40 U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater. EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC

41 U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater , Page 7-1, EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC

A6.1.1 Steady state

Where active remediation is being conducted, contaminant concentrations may decline for a period of time after groundwater treatment is terminated before leveling off at steady state conditions. The groundwater may not meet the criteria for attainment of cleanup levels if data from this transient decline are included in the analysis. This may also be true for other remedial actions, such as source removal.

In these situations, it is recommended that collection of sampling data to demonstrate the attainment of cleanup standards be delayed until conditions resembling steady state are attained (i.e., use data obtained over at least three years after contaminant concentrations have stopped declining). Alternatively, begin collecting the data after concentrations have declined below cleanup standards, even if steady state conditions have not yet been achieved.

Plots of contaminant concentrations over time may provide sufficient information to decide when to begin collecting data for demonstrating compliance with cleanup standards. However, if the plots do not provide a clear and unambiguous basis for making the decision, more objective statistical methods are available in the EPA guidance.[42]

A6.1.2 Frequency and duration of groundwater sampling

For the purpose of demonstrating compliance with cleanup standards, samples should be collected from each well where cleanup standards apply over a period of at least three years. No more than one sample should be collected per month with at least one sample collected per quarter.[43]

A6.1.3 Attainment of cleanup standards

The decision on whether cleanup levels are met is based on the comparison of the upper 95% confidence limit on the mean, calculated from the sampling data, with the cleanup level. In addition to this criterion concerning the mean concentration, compliance with a MTCA cleanup level also requires that no sample concentration can exceed twice the cleanup level, and that less than 10% of the samples can exceed the cleanup level (Section 1.1). A separate analysis must be performed with data obtained from each well over the monitoring period of at least three years.

Data from different wells may not be combined. Consult the *Statistical Guidance for Ecology Site Managers* for further information.

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[42] U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater, Chapter 7, EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC.

[43] The period of three years is based on requirements for corrective actions at hazardous waste facilities in the Dangerous Waste Regulations (Chapter 173-303-645(7)(c)), and is also found in Chapter 5 (Subpart E. Ground-water Monitoring and Corrective Action) of the Solid Waste Disposal Facility Criteria Technical Manual, Section 5.21 (Implementation of the Corrective Action Program. 40 CFR §258.58 (e)-(g))

A6.2 Confirmational monitoring

Confirmational monitoring is conducted to "confirm the long-term effectiveness of the interim action or cleanup action once cleanup standards and, if appropriate, other performance standards have been attained."[44]

Failure to achieve a permanent cleanup can occur for various reasons. For example, contaminated soil that was overlooked during a cleanup may eventually recontaminate the groundwater and the problem should be detected during confirmational monitoring. At a site where containment, rather than cleanup, of a hazardous substance is the chosen remedy, failure of the containment structure could eventually lead to recontamination of the groundwater. To guard against this possibility, it may be necessary to continue confirmational monitoring indefinitely.

Data gathered from compliance monitoring are useful for evaluating the performance of a cleanup action such as source removal or containment. To make use of these data during confirmational monitoring, trend analysis (Section A6.1, "Deciding when to end treatment") is important to evaluate data from individual sampling events relative to long term trends.

For sites which are subject to periodic review (no less frequently than every five years), a confirmational monitoring plan must be prepared and implemented until Ecology determines that periodic reviews are no longer required. A site is subject to periodic review if hazardous substances remain at concentrations which exceed Method A or Method B cleanup levels, or if conditional points of compliance have been established.[45] Section A6.2.1 provides guidance on confirmational monitoring at these sites.

Confirmational monitoring is also required at sites which are not subject to periodic review.[46] Guidance for these sites is provided in Section A6.2.2.

A6.2.1 Sites subject to periodic review

Ecology will provide site-specific guidance on compliance monitoring plans for sites that are subject to periodic review.

For municipal solid waste landfills, compliance monitoring will normally be required until wastes and contaminants decompose and no longer represent a threat to groundwater. This will typically be 20 to 40 years after site closure.

For other containment sites with waste or soil contaminants that do not decompose, compliance monitoring will need to continue indefinitely.

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44 WAC 173-340-410(1)(c)

45 WAC 173-340-420(1)

46 WAC 173-340-410(2)

For long term compliance monitoring, a suggested schedule would be:

First 5 years: Quarterly monitoring, evaluate data at 5 year review. If site conditions appear stabilized then:

Yrs 5-10: Biannual monitoring (covering the wet and dry seasons, or site specific worst case conditions), evaluate data at 5 year review. If conditions appear stabilized, then:

Yrs 10-15: Annual monitoring (worst case time of year, based on historical data), evaluate data at 5 year review.

Yrs 15-20: Monitor once in years 17 and 20, evaluate at 5 year review.

Yr 20 on: Monitor once every 5 years, evaluate data at 5 year review. Monitoring should continue indefinitely until (1) waste or contamination has decomposed; (2) as long as a containment system (including a cap) is relied upon to protect groundwater; and (3) if there is no cap, soil and groundwater sampling shows no further migration of contaminants for at least 10 years (after year 20).

A6.2.2 Sites where periodic review is not required

A report to Ecology demonstrating that cleanup standards have been met must also analyze the performance monitoring data to show that the cleanup will be permanent. In some cases, visual inspection of the plotted data may be sufficient to establish that concentrations are not increasing. Where the plots do not provide a clear and unambiguous basis for making the decision, more objective statistical methods are available in the EPA guidance.[47]

After reviewing the report, Ecology may determine that the data obtained from performance monitoring are sufficient to show that attainment of cleanup standards will be permanent, or that further confirmational monitoring is required before a decision can be made. In the latter case, Ecology will provide site-specific guidance on sampling requirements.

[47] U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater, Section 9.7, EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC

A7.0 Alternate sampling proposals

Alternate performance or confirmational monitoring sampling procedures may be proposed if adequately supported by a site-specific analysis. Factors which should be considered in such an analysis include the velocity of groundwater flow; the minimum interval between sampling times required to obtain independent measurements, based on an analysis of serial correlations in the data; whether there are seasonal or other periodic changes in contaminant concentrations in the groundwater; and sampling requirements to detect trends in contaminant concentrations.[48]

A8.0 Area background

If contaminant concentrations in the groundwater are attributed to area background, rather than on- or off-site point sources, see comments in Section 3.0. Note that the definition of area background (Section 3.1) refers to concentrations "consistently" present (i.e., similar concentrations should be observed in both upgradient and downgradient wells).

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[48] For discussion, see EPA (1992), Section 8.2, and references cited therein

U.S. EPA. 1992. Methods for Evaluating the Attainment of Cleanup Standards - Volume 2: Groundwater. EPA 230-R-92-014. U.S. EPA Office of Policy, Planning and Evaluation, Washington, DC.

A9.0 Off-site source

If contaminant concentrations are attributed to an off-site source, the evidence presented should be supported by the following:

1. A site potentiometric surface map, with surveyed groundwater elevations must be provided. Additional maps are expected for those sites with water tables that are significantly influenced by seasonal climatic variations, well pumpage, or tidal fluctuation.

2. Utility corridors, drains, or other preferential flow pathways that may be transporting contaminants from an off-site source must be clearly annotated on a map.

3. Geologic cross-sections between upgradient and downgradient monitoring wells depicting the following: a) groundwater elevations, b) subsurface stratigraphy, and c) monitoring well construction details (screens, seals, pump setting). Verification of subsurface stratigraphy by other techniques, such as borehole geophysics, is encouraged.

4. A table summarizing all available groundwater sampling data. Data from multiple sampling events must be provided. Data from one sampling event will not be accepted as credible evidence of off-site contamination.

5. A brief summary, citing all relevant evidence, as to why it is proposed that contamination is originating from an off-site source.

APPENDIX II

Reference Information

PQLs as Cleanup Standards. **Washington Department of Ecology.**

Methods for Evaluating the Attainment of Cleanup Standards. U.S. EPA.

Vol. 1. Soils and Solid Media.
Vol. 2. Groundwater.

Only relevant sections from Vol. 1-2 of the EPA guidance are included here. To obtain the complete documents, contact the National Technical Information Service at (703) 487 4650.

DEPARTMENT OF ECOLOGY

November 24, 1993

Implementation Memo No. 3

TO: Interested Staff

FROM: Steve Robb SR
Toxics Cleanup Program

SUBJECT: PQLs as Cleanup Standards

ISSUES

Two issues have been raised with regard to the use of practical quantitation limits (PQLs) in setting cleanup levels:

- **The "legal" issue of PQLs as cleanup levels and whether or not PLPs have any long-term liability for sites cleaned up to the PQL level rather than the risk-based level. Can PLPs receive a covenant not to sue in these situations? Are they required to utilize institutional controls and conduct long-term monitoring?**

- **When risk-based compliance values are less than PQLs, what value is used in the risk summation calculation, the risk-based value or the PQL?**

I. LONG-TERM LIABILITY

The Model Toxics Control Act (MTCA) states, "Where cleanup levels are below the PQL, compliance with cleanup standards will be based upon the PQL" (WAC 173-340-700(6) Measuring compliance). Also stated in the rule, "If those situations arise and the practical quantitation limit is higher than the cleanup level for that substance, the cleanup level shall be considered to have been attained, subject to subsection (4) of this section...." (WAC 173-340-707(2) Analytical considerations). Therefore, the PQL becomes the compliance

value, and PLPs who attain the PQL are eligible for a covenant not to sue. WAC 173-340-707(4) places one additional burden, however, and that is a requirement for periodic review of the cleanup action in which the department, in reviewing the cleanup action, shall "...consider the availability of improved analytical techniques." Therefore, any covenant must have a reopener which would allow the department to take action if necessary.

Long-term monitoring is not required as long as the remedy does not specifically involve containment. However, it is possible that the remaining unquantified risk at a site could be sufficient to cause concern. This situation makes it very important for project managers to require PLPs to attempt to quantify those contaminants which have high PQLs. We need to avoid situations in which PLPs may leave unquantified contamination and that upon periodic review new analytical data demonstrates that further action is necessary. The rule supports the use of special analytical methods and/or institutional controls to address this situation.

WAC 173-340-707(3) gives project managers the flexibility to require special sampling and analytical methods. PQLs should not be used to justify unnecessarily high compliance levels. In cases where the risk-based cleanup level is less than the PQL, site managers should calculate, using the appropriate formula, the risk the contaminant would represent if it were present at the PQL concentration. As this risk approaches the $1x10^{-5}$ level, serious consideration should be given to use of surrogate measures of the hazardous substance or development of specialized sample collection and/or analysis techniques. If the risk posed by a contaminant concentration at the PQL level exceeds the $1x10^{-5}$ level, project managers should consider requiring special analytical methods which can quantify the contaminant concentration at least to the $1x10^{-5}$ level.

In support of this approach, the Responsiveness Summary (RS) acknowledges that in meeting its mission to protect human health and the environment, Ecology cannot ignore concentrations below current quantitation limits. In doing so, the RS states, we would be placing "...human health and the environment 'at the mercy of analytic quantitation limits' and would be inconsistent with the statute's overriding objectives" (p. 107).

Finally, WAC 173-340-440(1)(a) requires institutional controls "...when the department determines such controls are required to assure the continued protection of human health and the environment or the integrity of the cleanup action." In situations where the PQL is above cleanup levels (i.e. exceed the $1x10^{-5}$ level), project managers should evaluate the need for institutional controls, particularly if special analytical methods are inadequate.

II. RISK SUMMATION CALCULATIONS BASED ON PQLs

MTCA requires the development of cleanup levels that are protective of human health and the environment. For carcinogenic substances, protection is defined as a cumulative site risk that does not exceed 1 in 100,000 ($1x10^{-5}$). However, our inability to reliably measure some contaminant concentrations at calculated risk-based levels hinders our ability to measure total site risk.

In some situations the risk posed by a single contaminant at the PQL concentration outweighs the risk of all the other contaminants put together. Using such a PQL risk value in the risk summation calculation will negate the usefulness of both the risk summation and the $1x10^{-5}$ cumulative site risk requirement. In this situation, to calculate overall site risk, use the risk-based cleanup level rather than the PQL. The other contaminant concentrations can then be adjusted downward, as necessary, so the adjusted total site risk does not exceed $1x10^{-5}$. The final list of compliance levels should show the single contaminant at the PQL value and the other contaminants at their adjusted levels.

When adjusting individual cleanup levels to meet the one in a hundred thousand total risk standard at sites with multiple contaminants becomes necessary, do not adjust a contaminant below its PQL. For example, the cleanup level for trichloroethylene (TCE) in groundwater is 3.98 ppb and the PQL is 0.5 ppb. If higher cleanup levels for other compounds required the TCE cleanup level to be adjusted downward, it should not be adjusted below 0.5 ppb.

One final clarification regarding risk summation is warranted. Method B specifically establishes cleanup levels based on a risk of one in a million for individual carcinogenic contaminants. When multiple contaminants and/or multiple pathways of exposure are involved, MTCA allows for a cumulative site risk of no more than one in a hundred thousand (e.g., WAC 173-340-720(5)). **The one in a hundred thousand risk level is intended to serve as a cap, or ceiling, on the cumulative site risk at cleanup sites with multiple contaminants and is not a goal.**

For example, when the cumulative site risk total is $8x10^{-5}$, cleanup levels for individual constituents must be adjusted downward until the cumulative site risk is equal to or less than $1x10^{-5}$. Alternately, at sites where the total cumulative site risk is $8x10^{-6}$, for example, no downward adjustment is necessary, since the risk does not exceed $1x10^{-5}$. However, adjustment upward for individual contaminants is not permitted under MTCA since individual contaminants must still meet the $1x10^{-6}$ (or $1x10^{-5}$ for Method C) limit.

Risk Communication

How we portray risk to the public is important to the implementation of the rules. When cleanup levels are based on PQL values, Ecology site managers should explain that

technical limitations may prohibit us from measuring contaminants at levels that correspond to a risk of $1x10^{-6}$. This explanation should be part of the Cleanup Action Plan (CAP) and any public hearings where cleanup levels and risk are discussed. The CAP should include a list of risk-based levels as well as a list of the compliance levels.

Analytical Guidelines

- Know your expected PQLs. Communicate with your laboratory if you have any doubts, special expectations, or special analytical needs. Before your analytical work is requested, be sure that the results to be provided by your laboratory will meet your requirements.

- With the analytical results, the estimates of the PQLs for each sample matrix along with an explanation of how the PQL was determined should be provided by the laboratory.

- Appropriate quality assurance and quality control (QA/QC) data should be provided by the laboratory for all sets of samples.

What Are The PQLs?

There is no definitive list of PQLs. However, Ecology has put together tables of PQLs, MDLs (method detection limits), and comparisons to Method B numbers for groundwater, surface water, and soil. These tables are based on surveying published methods and laboratories. There are many factors that can produce a different PQL for one sample as compared to another. However, these tables can be useful guidance. Ecology refers you to the guidance for the use of the tables and also to a discussion on the meaning of PQLs. These are found as three additional parts to this memorandum. The four parts are:

Part I:	*Implementation Memo No. 3--PQLs as Cleanup Standards (this document)*
Part II:	*Guidance For The Use of Tables*
Part III:	*MDL, PQL, and Comparisons Tables*
Part IV:	*Appendix--Meaning of Quantitation Limits*

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GUIDANCE FOR THE USE OF TABLES: PRACTICAL QUANTITATION LIMITS (PQLS), METHOD DETECTION LIMIT (MDLS), AND PQL COMPARISONS TO METHOD B CLEANUP LEVELS

This guidance is Part II of four parts. They are:

Part I:	*Implementation Memo No. 3--PQLs as Cleanup Standards*
Part II:	*Guidance For The Use of Tables (this document)*
Part III:	*MDL, PQL, and Comparisons Tables*
Part IV:	*Appendix--Meaning of Quantitation Limits*

The Model Toxics Control Act (MTCA) provides human health risk-based cleanup levels for contaminants at cleanup sites. For certain compounds the risk-based values (Method B values) are less than the lowest levels which can be routinely quantified and reported by a laboratory. These lowest levels are known as the "practical quantitation limits" (PQLs). The "method detection limit" (MDL) is used mostly by the laboratory analyst and not usually reported, but can provide useful information to the site manager.

To provide a cleanup site manager with information on PQLs and the MDLs, we prepared tables of these values including a comparison to the MTCA Method B levels.

The MDL and/or PQL for a substance can be useful when requesting analytical work to verify it is possible to achieve the desired analytical limit. With information in these tables about the MDLs and PQLs for different analytical methods the site manager can choose the appropriate method and avoid wasteful analytical work that does not provide the desired limit. The site manager can also use these tables to check data to verify that the reported analytical limit is indeed reasonable.

What if the PQL exceeds the MTCA cleanup level? Ecology may require the use of surrogate measures of contamination; the use or development of specialized sample collection or analysis techniques to improve the method detection limit or practical quantitation limits for the hazardous substances at the site; monitoring to assure the concentration of a hazardous substance does not exceed detectable levels; or institutional controls in the event that the uncertainty posed by the limits of technology is unacceptable. Ecology also shall consider the availability of improved analytical techniques when performing periodic reviews. Subsequent to those reviews, the department may require the use of improved analytical techniques with lower practical quantitation limits and other appropriate actions (see WAC 173-340-707 Analytical considerations).

The PQLs listed in the tables are from published methods and confirmed by a number of laboratories. However, the PQLs for a given set of samples may vary for numerous reasons (see a discussion on PQLs in Part IV, Appendix).

The attached PQL/MDL tables are not intended to replace Method B values or be used as "default cleanup values." They should be used for the purposes described above.

It is suggested at the time of sample submittal that the site manager discuss with the laboratory the available analytical methods. A particular method should be chosen to provide the required degree of protection as well as to keep analytical costs as low as possible. This is especially important when there are multiple contaminants but one contaminant "drives" the cleanup level. Choosing a method with a PQL lower than the cleanup level, if possible, will be very important.

The tables are for water (ground- and surface water) and soil. The following is a description of the columns found on the tables:

CAS: Chemical Abstract Service registry number; a unique number assigned to a specific chemical.

Chemical Name: The chemicals listed in the PQL tables were derived from the "Washington Ranking Method for Site Hazard Assessment." *Not all chemicals from the "Cleanup Levels and Risk Calculation" (CLARC II) database are contained within the PQL tables.*

Names of organic chemicals frequently are preceded by numbers or certain letters used to describe the structure of the chemical. For purposes of indexing chemical names, this structural information is placed at the end of the chemical name.

Method: Some of the method numbers listed in this column refer to analytical methods listed in "Test Methods for Evaluating Solid Waste", US EPA SW 846. The 3000 series number refers to procedures used to prepare sample for analysis; 7000 series numbers refer to atomic absorption test methods; 8000 - 8100 series numbers refer to gas chromatographic methods; 8310 series numbers refer to high pressure liquid chromatography methods; and 9000 series numbers refer to colorimetric (spectrophotometric methods).

Another source of analytical methods is the Code of Federal Regulations, Vol. 40, Parts 136 and 141 for establishing test procedures for the analysis of pollutants. The 200 series numbers apply to metals analysis; the 500 series numbers to the analysis of organics in potable water; and the 600 series numbers to the analysis of organics compounds in drinking and waste water.

These are the primary sources of methods used by Ecology. These and others are identified in WAC 173-340-830 Analytical procedures.

Detector: The detector is the device that responds to the presence of the chemical after separation. Detectors vary in sensitivity to the individual chemicals.

AA	Atomic absorption spectroscopy
Color	Colorimetric method, spectrophotometry
HPLC	High pressure liquid chromatography
GC ECD	Separation of contaminant mixtures into individual components using gas chromatography and an electron capture detector
GC FID	Separation of contaminant mixtures into individual components using gas chromatography and a flame ionization detector
GC Hall	Separation of contaminants mixtures into individual components using gas chromatography and a Hall electrolytic conductivity detector
GC MS	Separation of contaminant mixtures into individual components using gas chromatography and mass spectrometry
GC NP	Separation of contaminant mixtures into individual components using gas chromatography and a nitrogen/ phosphorous detector
GC PID	Separation of contaminant mixtures into individual components using gas chromatography and a photoionization detector
GFAA	Analysis by graphite furnace atomic absorption
GHAA	Analysis by gaseous hydride atomic absorption
ICP	Analysis by inductively coupled plasma emission

MDL: Method Detection Limit: The minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero. The MDL values provided in the tables are values derived from WAC 173-340-830(4); e.g., *Test Methods for Evaluating Solid Waste*, U.S. EPA, SW-846, and compiled by PTI Environmental Services.

PQL: Practical Quantitation Limit: This is the concentration that can be reliably measured within specified limits during routine laboratory operating conditions using Ecology approved methods (see Part IV). The PQL values provided in the tables are values derived from WAC 173-340-830(4); e.g., *Test Methods for Evaluating Solid Waste*, U.S. EPA, SW-846, and compiled

by PTI Environmental Services. In cases where there are no known PQL values (such as from the Federal Registry 40 CFR 136 & 141; 500 and 600 series), a factor of 10 times the MDL is used for the PQL value.

NOTE: "Table I Water" is reported in ug/l (ppb), "Table II Soil" is reported in mg/kg (ppm).

PQL Range: The range of thirteen responses out of a survey conducted by Ecology of fifty independent environmental laboratories. The survey was conducted to determine the range of PQLs achievable by specific matrixes, methods, and detectors. The laboratories surveyed routinely conduct these types of environmental analyses.

In some instances (indicated by a "**thumbs-up**" icon in the tables), the laboratories were able to attain a PQL lower than the federal PQL. For example, Table II for soil indicates antimony using Method 6010 attains a PQL range of 1.5 - 10 mg/kg with a PQL of 16 mg/kg.

Method B: The $1x10^{-6}$ (for carcinogens) Method B values are provided in Tables I and II for purposes of comparison with MDL and PQL values. Only carcinogens are included because there are frequently both PQL and Method B values for the same compound, and non-carcinogens are usually higher and often do not list both a Method B value and a PQL.

PQL > GW or SW or Soil Method B These columns compare the PQL with the Method B groundwater (GW); surface water (SW); or soil formula values in their respective columns/tables.

Below are the following displayed conditions:

A **blank cell** indicates either (1) the Method B values is greater than the PQL, or (2) there is no PQL value available for comparison;

The "**bomb**" icon indicates the PQL is greater than the Method B formula value;

The "**flag**" icon indicates there is currently no Method B value in Ecology's Cleanup Levels and Risk Calculations (CLARC II) available for comparison.

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag = na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag = na)
83-32-9	acenaphthene	625	Wastewater	GC/MS	1.9	19		0.8 - 19				
83-32-9	acenaphthene	1625	Wastewater		10	100		0.8 - 100				
83-32-9	acenaphthene	8270	Groundwater	GC/MS		10		0.8 - 10				
83-32-9	acenaphthene	610/8310	Waste/Groundwater	HPLC	1.8	18		0.8 - 18				
208-96-8	acenaphthylene	625	Wastewater	GC/MS	3.5	35		1 - 35	n/c		n/c	
208-96-8	acenaphthylene	8270	Groundwater	GC/MS		10		1 - 10	n/c		n/c	
208-96-8	acenaphthylene	610/8310	Waste/Groundwater	HPLC	2.3	23		1 - 23	n/c		n/c	
67-64-1	acetone	8240	Groundwater	GC/MS		10		1 - 50				
107-02-8	acrolein	603	Wastewater	GC-FID	0.6	6						
107-02-8	acrolein	8030	Groundwater	GC-FID	0.7	7		1 - 50				
79-06-1	acrylamide	8015	Groundwater	GC-FID					9.72E-3			
107-13-1	acrylonitrile	603	Wastewater	GC-FID	0.5	5		1 - 10	8.10E-2	*	4.00E-1	*
107-13-1	acrylonitrile	8030	Groundwater	GC-FID	0.5	5		1 - 20	8.10E-2	*	4.00E-1	*
15972-60-8	alachlor	102	Wastewater	GC-ECD	0.2	2			1.08E+0	*		
15972-60-8	alachlor	505.2	Drinking Water	GC-ECD	0.225	2			1.08E+0	*		
15972-60-8	alachlor	507	Drinking Water	GC-N/P	0.38	4			1.08E+0	*		
116-06-3	aldicarb	531.1	Drink/Groundwater	HPLC	1	10						
309-00-2	aldrin	617	Wastewater	GC-ECD	0.009	0.09			5.15E-3	*	8.16E-5	*
309-00-2	aldrin	625	Wastewater	GC/MS	1.9	19			5.15E-3	*	8.16E-5	*
309-00-2	aldrin	505/508	Drinking Water	GC-ECD	0.075	0.8			5.15E-3	*	8.16E-5	*
309-00-2	aldrin	608/8080	Groundwater	GC-ECD	0.004	0.04		0.005 - 0.04	5.15E-3	*	8.16E-5	*
62-53-3	aniline	8270	Groundwater	GC/MS		10		2 - 10	1.54E+1			
120-12-7	anthracene	625	Wastewater	GC/MS	1.9	19		1 - 19				
120-12-7	anthracene	8270	Groundwater	GC/MS		10		1 - 10				
120-12-7	anthracene	610/8310	Waste/Groundwater	HPLC	0.013	0.1		0.1 - 1				
7440-36-0	antimony	204.1	Water	FAA	200	2000						
7440-36-0	antimony	6010	Groundwater	ICP	32	320		10 - 60				
7440-36-0	antimony	204.2/7041	Groundwater	GFAA	3	30						
140-57-8	aramite	8270	Groundwater	GC/MS		20		2 - 20	3.50E+0	*		
12674-11-2	Aroclor 1016 (PCB)	505	Drinking Water	GC-ECD	0.08	0.8						
12674-11-2	Aroclor 1016 (PCB)	608/8080	Waste/Groundwater	GC-ECD		0.65		0.05 - 0.65				
11104-28-2	Aroclor 1221 (PCB)	505	Drinking Water	GC-ECD	15	150			n/c		n/c	
11104-28-2	Aroclor 1221 (PCB)	508	Drinking Water	GC-ECD	0.14	1			n/c		n/c	
11104-28-2	Aroclor 1221 (PCB)	608/8080	Waste/Groundwater	GC-ECD		0.65		0.05 - 1	n/c		n/c	
11141-16-5	Aroclor 1232 (PCB)	505	Drinking Water	GC-ECD	0.48	5			n/c		n/c	
11141-16-5	Aroclor 1232 (PCB)	508	Drinking Water	GC-ECD	0.23	2			n/c		n/c	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag = na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag = na)
11141-16-5	Aroclor 1232 (PCB)	608/8080	Waste/Groundwater	GC-ECD		0.65		0.05 - 1	n/c		n/c	
53469-21-9	Aroclor 1242 (PCB)	505	Drinking Water	GC-ECD	0.31	3			n/c		n/c	
53469-21-9	Aroclor 1242 (PCB)	508	Drinking Water	GC-ECD	0.21	2			n/c		n/c	
53469-21-9	Aroclor 1242 (PCB)	608/8080	Waste/Groundwater	GC-ECD	0.065	0.65		0.05 - 1	n/c		n/c	
12672-29-6	Aroclor 1248 (PCB)	505	Drinking Water	GC-ECD	0.102	1			n/c		n/c	
12672-29-6	Aroclor 1248 (PCB)	508	Drinking Water	GC-ECD	0.15	2			n/c		n/c	
12672-29-6	Aroclor 1248 (PCB)	608/8080	Waste/Groundwater	GC-ECD		1.3		0.05 - 1.3	n/c		n/c	
11097-69-1	Aroclor 1254 (PCB)	505	Drinking Water	GC-ECD	0.102	1			n/c		n/c	
11097-69-1	Aroclor 1254 (PCB)	508	Drinking Water	GC-ECD	0.14	1			n/c		n/c	
11097-69-1	Aroclor 1254 (PCB)	608/8080	Waste/Groundwater	GC-ECD		1.3		0.05 - 1.3	n/c		n/c	
11096-82-5	Aroclor 1260 (PCB)	505	Drinking Water	GC-ECD	0.189	2			n/c		n/c	
11096-82-5	Aroclor 1260 (PCB)	508	Drinking Water	GC-ECD	0.14	1			n/c		n/c	
11096-82-5	Aroclor 1260 (PCB)	608/8080	Waste/Groundwater	GC-ECD					n/c		n/c	
7440-38-2	arsenic	206.2	Water	GFAA	1	10		0.01 - 100	5.00E-2		8.42E-2	
7440-38-2	arsenic	206.3	Water	FAA	2	20			5.00E-2		8.42E-2	
7440-38-2	arsenic	7061	Groundwater	GH-AA	2	20			5.00E-2		8.42E-2	
7440-38-2	arsenic	200.7/6010	Groundwater	ICP	53	530			5.00E-2		8.42E-2	
1332-21-4	asbestos	NPDES-400	Wastewater									
1912-24-9	atrazine	619	Wastewater	GC/NP		5		0.9 - 5	3.98E-1			
103-33-3	azobenzene	8270	Groundwater	GC/MS		330		52 - 330	7.95E-1			
56-55-3	benz[a]anthracene	625	Wastewater	GC/MS	7.8	78		1 - 78	1.20E-2		2.96E-2	
56-55-3	benz[a]anthracene	8270	Groundwater	GC/MS		10		1 - 10	1.20E-2		2.96E-2	
56-55-3	benz[a]anthracene	610/8310	Waste/Groundwater	HPLC	0.013	0.1		0.1 - 1	1.20E-2		2.96E-2	
71-43-2	benzene	502.2	Drinking Water	GC-PID	0.01	0.1			1.51E+0		4.30E+1	
71-43-2	benzene	503.1	Drinking Water	GC-PID	0.02	0.2			1.51E+0		4.30E+1	
71-43-2	benzene	524.1	Drinking Water	GC/MS	0.1	1			1.51E+0		4.30E+1	
71-43-2	benzene	524.2	Drinking Water	GC/MS	0.04	0.4			1.51E+0		4.30E+1	
71-43-2	benzene	602	Wastewater	GC-PID	0.2	2			1.51E+0		4.30E+1	
71-43-2	benzene	624	Wastewater	GC/MS	4.4	44			1.51E+0		4.30E+1	
71-43-2	benzene	8020	Groundwater	GC-PID	0.2	2		0.5 - 10	1.51E+0		4.30E+1	
71-43-2	benzene	8240	Groundwater	GC/MS		5		0.5 - 10	1.51E+0		4.30E+1	
92-87-5	benzidine	605	Wastewater	HPLC	0.08	0.8			3.80E-4		3.22E-4	
92-87-5	benzidine	625	Wastewater	GC/MS	44	440			3.80E-4		3.22E-4	
50-32-8	benzo[a]pyrene	625	Wastewater	GC/MS	2.5	25		1 - 25	1.20E-2		2.96E-2	
50-32-8	benzo[a]pyrene	8270	Groundwater	GC/MS		10		2 - 10	1.20E-2		2.96E-2	
50-32-8	benzo[a]pyrene	610/8310	Waste/Groundwater	HPLC	0.023	0.2		0.2 - 2	1.20E-2		2.96E-2	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
205-99-2	benzo[b]fluoranthene	625	Wastewater	GC/MS	4.8	48			1.20E-2		2.96E-2	
205-99-2	benzo[b]fluoranthene	8270	Groundwater	GC/MS		10		3 - 10	1.20E-2		2.96E-2	
205-99-2	benzo[b]fluoranthene	610/8310	Waste/Groundwater	HPLC	0.018	0.2		0.2 - 3	1.20E-2		2.96E-2	
191-24-2	benzo[g,h,i]perylene	625	Wastewater	GC/MS	4.1	41			n/c		n/c	
191-24-2	benzo[g,h,i]perylene	8270	Groundwater	GC/MS		10		2 - 10	n/c		n/c	
191-24-2	benzo[g,h,i]perylene	610/8310	Waste/Groundwater	HPLC	0.076	0.8		0.8 - 1	n/c		n/c	
207-08-9	benzo[k]fluoranthene	625	Wastewater	GC/MS	2.5	25			1.20E-2		2.96E-2	
207-08-9	benzo[k]fluoranthene	8270	Groundwater	GC/MS		10		0.2 - 10	1.20E-2		2.96E-2	
207-08-9	benzo[k]fluoranthene	610/8310	Waste/Groundwater	HPLC	0.017	0.2		0.2 - 3	1.20E-2		2.96E-2	
65-85-0	benzoic acid	8270	Groundwater	GC/MS		50		6 - 50				
98-07-7	benzotrichloride	8270	Groundwater	GC/MS		10			6.73E-3			
100-51-6	benzyl alcohol	8270	Groundwater	GC/MS		20		2 - 20				
100-44-7	benzyl chloride	8240	Groundwater	GC/MS		100		1 - 100	2.57E-1			
7440-41-7	beryllium	6010	Groundwater	ICP	0.3	3		0.01 - 5	2.03E-2		7.93E-2	
7440-41-7	beryllium	7090	Water	FAA	5	50			2.03E-2		7.93E-2	
7440-41-7	beryllium	7091	Groundwater	GFAA	0.2	2			2.03E-2		7.93E-2	
111-91-1	bis(2-chloroethoxy)methane	611	Wastewater	GC-Hall	0.5	5			n/c		n/c	
111-91-1	bis(2-chloroethoxy)methane	625	Wastewater	GC/MS	5.3	53			n/c		n/c	
111-91-1	bis(2-chloroethoxy)methane	8270	Groundwater	GC/MS		10		2 - 10	n/c		n/c	
111-44-4	bis(2-chloroethyl)ether (BCEE)	611	Wastewater	GC-Hall	0.3	3			3.98E-2		8.54E-1	
111-44-4	bis(2-chloroethyl)ether (BCEE)	625	Wastewater	GC/MS	5.7	57			3.98E-2		8.54E-1	
111-44-4	bis(2-chloroethyl)ether (BCEE)	8270	Groundwater	GC/MS		10		1 - 10	3.98E-2		8.54E-1	
39638-32-9	bis(2-chloroisopropyl)ether	611	Wastewater	GC-Hall	0.8	8						
39638-32-9	bis(2-chloroisopropyl)ether	625	Wastewater	GC/MS	5.7	57						
39638-32-9	bis(2-chloroisopropyl)ether	8270	Groundwater	GC/MS		10		4 - 10				
117-81-7	bis(2-ethylhexyl) phthalate (BEHI	606	Wastewater	GC-ECD	2	20			6.25E+0		3.56E+0	
117-81-7	bis(2-ethylhexyl) phthalate (BEHI	625	Wastewater	GC/MS	2.5	25			6.25E+0		3.56E+0	
117-81-7	bis(2-ethylhexyl) phthalate (BEHI	8270	Groundwater	GC/MS		10		1 - 10	6.25E+0		3.56E+0	
542-88-1	bis(chloromethyl)ether (BCME)	611	Wastewater	GC-Hall	0.8	10		4 - 10	1.99E-4			
75-27-4	bromodichloromethane (THM)	502.1	Drinking Water	GC-PID	0.003	0.03			7.06E-1		2.79E+1	
75-27-4	bromodichloromethane (THM)	502.2	Drinking Water	GC-ECD	0.02	0.2			7.06E-1		2.79E+1	
75-27-4	bromodichloromethane (THM)	524.1	Drinking Water	GC/MS	0.5	5			7.06E-1		2.79E+1	
75-27-4	bromodichloromethane (THM)	524.2	Drinking Water	GC/MS	0.08	0.8			7.06E-1		2.79E+1	
75-27-4	bromodichloromethane (THM)	601	Wastewater	GC-Hall	0.1	1			7.06E-1		2.79E+1	
75-27-4	bromodichloromethane (THM)	624	Wastewater	GC/MS	2.2	22			7.06E-1		2.79E+1	
75-27-4	bromodichloromethane (THM)	8010	Groundwater	GC-Hall	0.1	1		0.5 - 2	7.06E-1		2.79E+1	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag = na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag = na)
75-27-4	bromodichloromethane (THM)	8240	Groundwater	GC/MS		5		0.2 - 10	7.06E-1		2.79E+1	
75-25-2	bromoform (THM)	502.1	Drinking Water	GC-PID	0.05	0.5			5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	502.2	Drinking Water	GC-ECD	1.6	16			5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	524.1	Drinking Water	GC/MS	0.7	7			5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	524.2	Drinking Water	GC/MS	0.12	1			5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	601	Wastewater	GC-Hall	0.2	2			5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	624	Wastewater	GC/MS	4.7	47			5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	8010	Groundwater	GC-Hall	0.2	2		1 - 2	5.54E+0		2.19E+2	
75-25-2	bromoform (THM)	8240	Groundwater	GC/MS		5		2 - 10	5.54E+0		2.19E+2	
101-55-3	bromophenyl phenyl ether;4-	611	Wastewater	GC-Hall	2.3	23			n/c		n/c	
101-55-3	bromophenyl phenyl ether;4-	625	Wastewater	GC/MS	1.9	19			n/c		n/c	
101-55-3	bromophenyl phenyl ether;4-	8270	Groundwater	GC/MS		10		0.6 - 10	n/c		n/c	
85-68-7	butyl benzyl phthalate	625	Wastewater	GC/MS	2.5	25						
85-68-7	butyl benzyl phthalate	8060	Waste/Groundwater	GC-ECD	0.34	3		3 - 10				
85-68-7	butyl benzyl phthalate	8270	Groundwater	GC/MS		10		1 - 10				
85-68-7	butyl benzyl phthalate	606/8060	Waste/Groundwater	GC-FID	15	150		10 - 150				
7440-43-9	cadmium	200.7/6010	Water/Groundwater	ICP	4	40		0.01 - 100				
7440-43-9	cadmium	213.1/7130	Water/Groundwater	FAA	5	50						
7440-43-9	cadmium	213.2/7131	Water/Groundwater	GFAA	0.1	1						
86-74-8	carbazole	8270	Groundwater	GC/MS		10		2 - 10	4.38E+0			
1563-66-2	carbofuran	531.1	Drink/Groundwater	HPLC	1.5	15						
1563-66-2	carbofuran	632	Wastewater	GC-NP	5.0E	50						
1563-66-2	carbofuran	8270	Groundwater	GC/MS		10		1 - 10				
75-15-0	carbon disulfide	8240	Groundwater	GC/MS		100		1 - 100				
56-23-5	carbon tetrachloride	502.1	Drinking Water	GC-PID	0.003	0.03			3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	502.2	Drinking Water	GC-ECD	0.01	0.1			3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	524.1	Drinking Water	GC/MS	0.3	3			3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	524.2	Drinking Water	GC/MS	0.21	2			3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	601	Wastewater	GC-Hall	0.12	1			3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	624	Wastewater	GC/MS	2.8	28			3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	8010	Groundwater	GC-Hall	0.12	1		1 - 10	3.37E-1		2.66E+0	
56-23-5	carbon tetrachloride	8240	Groundwater	GC/MS		5		1 - 10	3.37E-1		2.66E+0	
57-74-9	chlordane	505	Drinking Water	GC-ECD	0.14	1		0.1 - 1.4	6.73E-2		3.54E-4	
57-74-9	chlordane	608/8080	Waste/Groundwater	GC-ECD	0.014	0.14		0.005 - 0.5	6.73E-2		3.54E-4	
	chlordane; alpha	505	Drinking Water	GC-ECD	0.006	0.06		0.005 - 0.06	n/c		n/c	
	chlordane; alpha	508	Drinking Water	GC-ECD	0.002	0.015			n/c		n/c	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

◆ Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)	◆	LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	◆* PQL > GW Method B (flag = na)	Method B SW Value (µg/L) - C	◆* PQL > SW Method B (flag = na)
	chlordane; gamma	505	Drinking Water	GC-ECD	0.012	0.12			n/c		n/c	
	chlordane; gamma	508	Drinking Water	GC-ECD	0.002	0.015			n/c		n/c	
3165-93-3	chloro-2-methylaniline hydrochlorid	8270	Groundwater	GC/MS		10		1 - 10	1.90E-1	◆*		
95-69-2	chloro-2-methylaniline;4-	8270	Groundwater	GC/MS		10		1 - 10	1.51E-1	◆*		
59-50-7	chloro-3-methylphenol;4-	625	Wastewater	GC/MS	3	30		4 - 30	n/c		n/c	
59-50-7	chloro-3-methylphenol;4-	8040	Groundwater	GC-ECD	1.8	18		4 - 18	n/c		n/c	
59-50-7	chloro-3-methylphenol;4-	8270	Groundwater	GC/MS		20		2 - 20	n/c		n/c	
59-50-7	chloro-3-methylphenol;4-	604/8040	Waste/Groundwater	GC-FID	0.36	4		1 - 4	n/c		n/c	
106-47-8	chloroaniline;4-	8270	Groundwater	GC/MS		20		4 - 20				
108-90-7	chlorobenzene	502.1	Drinking Water	GC-PID	0.005	0.05						
108-90-7	chlorobenzene	502.2	Drinking Water	GC-ECD	0.01	0.1						
108-90-7	chlorobenzene	503.1	Drinking Water	GC-ECD	0.004	0.04						
108-90-7	chlorobenzene	524.1	Drinking Water	GC/MS	0.1	1						
108-90-7	chlorobenzene	524.2	Drinking Water	GC/MS	0.04	0.4						
108-90-7	chlorobenzene	601	Wastewater	GC-Hall	0.25	3						
108-90-7	chlorobenzene	602	Wastewater	GC-PID	0.2	2						
108-90-7	chlorobenzene	624	Wastewater	GC/MS	6	60						
108-90-7	chlorobenzene	8010	Groundwater	GC-Hall	0.25	3		1.2 - 10				
108-90-7	chlorobenzene	8020	Groundwater	GC-PID	0.2	2		0.5 - 10				
108-90-7	chlorobenzene	8240	Groundwater	GC/MS		5		0.5 - 10				
124-48-1	chlorodibromomethane	8240	Groundwater	GC/MS		5		1 - 10	5.21E-1	◆*	2.06E+1	
75-00-3	chloroethane	502.1	Drinking Water	GC-PID	0.008	0.08						
75-00-3	chloroethane	502.2	Drinking Water	GC-ECD	0.1	1						
75-00-3	chloroethane	524.1	Drinking Water	GC/MS								
75-00-3	chloroethane	524.2	Drinking Water	GC/MS	0.1	1						
75-00-3	chloroethane	601	Wastewater	GC-Hall	0.52	5						
75-00-3	chloroethane	624	Wastewater	GC/MS								
75-00-3	chloroethane	8010	Groundwater	GC-Hall	0.52	5		1 - 10				
75-00-3	chloroethane	8240	Groundwater	GC/MS		10		1 - 10				
110-75-8	chloroethyl vinyl ether;2-	601	Wastewater	GC-Hall	0.13	1			n/c		n/c	
110-75-8	chloroethyl vinyl ether;2-	624	Wastewater	GC/MS					n/c		n/c	
110-75-8	chloroethyl vinyl ether;2-	8010	Groundwater	GC-Hall	0.13	1		1 - 10	n/c		n/c	
110-75-8	chloroethyl vinyl ether;2-	8240	Groundwater	GC/MS		10		1 - 20	n/c		n/c	
67-66-3	chloroform	502.2	Drinking Water	GC-ECD	0.02	0.2			7.17E+0		2.83E+2	
67-66-3	chloroform	524.1	Drinking Water	GC/MS	0.2	2			7.17E+0		2.83E+2	
67-66-3	chloroform	524.2	Drinking Water	GC/MS	0.03	0.3			7.17E+0		2.83E+2	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

◆ Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)	◆	LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	◆* PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	◆* PQL > SW Method B (flag=na)
67-66-3	chloroform	601	Wastewater	GC-Hall	0.05	0.5			7.17E+0		2.83E+2	
67-66-3	chloroform	624	Wastewater	GC/MS	1.6	16			7.17E+0	◆*	2.83E+2	
67-66-3	chloroform	8010	Groundwater	GC-Hall	0.05	0.5		0.2 - 2	7.17E+0		2.83E+2	
67-66-3	chloroform	8240	Groundwater	GC/MS		5		1 - 5	7.17E+0		2.83E+2	
74-87-3	chloromethane	502.1	Drinking Water	GC-PID	0.01	0.1			3.37E+0		1.33E+2	
74-87-3	chloromethane	502.2	Drinking Water	GC-ECD	0.03	0.3			3.37E+0		1.33E+2	
74-87-3	chloromethane	524.1	Drinking Water	GC/MS	0.13	1			3.37E+0		1.33E+2	
74-87-3	chloromethane	524.2	Drinking Water	GC/MS	0.13	1			3.37E+0		1.33E+2	
74-87-3	chloromethane	601	Wastewater	GC-Hall	0.08	0.8			3.37E+0		1.33E+2	
74-87-3	chloromethane	624	Wastewater	GC/MS	0.08	0.8			3.37E+0		1.33E+2	
74-87-3	chloromethane	8010	Groundwater	GC-Hall	0.08	0.8		0.8 - 2	3.37E+0		1.33E+2	
74-87-3	chloromethane	8240	Groundwater	GC/MS		10		1 - 10	3.37E+0	◆*	1.33E+2	
91-58-7	chloronaphthalene;2-	625	Wastewater	GC/MS	1.9	19			n/c	⚐	n/c	⚐
91-58-7	chloronaphthalene;2-	8270	Groundwater	GC/MS		10		1 - 100	n/c	⚐	n/c	⚐
91-58-7	chloronaphthalene;2-	612/8120	Waste/Groundwater	GC-ECD	0.94	9		1 - 9	n/c	⚐	n/c	⚐
88-73-3	chloronitrobenzene;o-	8270	Groundwater	GC/MS					3.50E+0			
100-00-5	chloronitrobenzene;p-	8270	Groundwater	GC/MS					4.86E+0			
95-57-8	chlorophenol;2-	625	Wastewater	GC/MS	3.3	33		4 - 33				
95-57-8	chlorophenol;2-	8040	Groundwater	GC-ECD	0.58	6		4 - 6				
95-57-8	chlorophenol;2-	8270	Groundwater	GC/MS		10		4 - 10				
95-57-8	chlorophenol;2-	604/8040	Waste/Groundwater	GC-FID	0.31	3		1 - 4				
7005-72-3	chlorophenyl phenyl ether;4-	611	Wastewater	GC-Hall	3.9	39			n/c	⚐	n/c	⚐
7005-72-3	chlorophenyl phenyl ether;4-	625	Wastewater	GC/MS	4.2	42			n/c	⚐	n/c	⚐
7005-72-3	chlorophenyl phenyl ether;4-	8270	Groundwater	GC/MS		10		1 - 10	n/c	⚐	n/c	⚐
1897-45-6	chlorthalonil	508	Drinking Water	GC-ECD	0.025	10		0.005 - 10	7.95E+0	◆*		
16065-83-1	chromium(III) NOTE: Total Cr (sub	218.2	Water	GFAA	1	10		5 - 10				
16065-83-1	chromium(III) NOTE: Total Cr (sub	7190	Waste/Groundwater	FAA	50	500		10 - 500				
16065-83-1	chromium(III) NOTE: Total Cr (sub	7191	Waste/Groundwater	GFAA	1	10						
18540-29-9	chromium(VI)	7195	Groundwater	PCP/AA	5	50						
18540-29-9	chromium(VI)	7196	Groundwater	Color	10	100						
18540-29-9	chromium(VI)	7197	Water	MBK/AA	1	10		10 - 50				
218-01-9	chrysene	625	Wastewater	GC/MS	2.5	25			1.20E-2	◆*	2.96E-2	◆*
218-01-9	chrysene	8270	Groundwater	GC/MS		10		1 - 10	1.20E-2	◆*	2.96E-2	◆*
218-01-9	chrysene	610/8310	Waste/Groundwater	HPLC	0.15	2		2 - 10	1.20E-2	◆*	2.96E-2	◆*
7440-50-8	copper	200.7/6010	Water/Groundwater	ICP	6	60	◆	10 - 50				
7440-50-8	copper	220.1/7210	Water/Groundwater	AA	20	200						

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
7440-50-8	copper	220.2/7211	Water/Groundwater	AA	1	10						
	creosote (aromatic hydrocarbon cc	8270	Groundwater	GC/MS		10		2 - 10	n/c		n/c	
8001-58-9	creosote (phenolic components)	8270	Groundwater	GC/MS		10		2 - 10				
108-39-4	cresol;m-	8270	Groundwater	GC/MS		10		2 - 10				
95-48-7	cresol;o-	8270	Groundwater	GC/MS		10		2 - 10				
106-44-5	cresol;p-	8270	Groundwater	GC/MS		10		2 - 10				
57-12-5	cyanide	9010	Waste/Groundwater	Color	20	200		10 - 50				
57-12-5	cyanide	9012	Waste/Groundwater	A-Color	5	50						
75-99-0	dalapon, sodium salt	615/8150	Waste/Groundwater	GC-ECD	5.8	58		5 - 58				
94-82-6	DB;2,4-	515.1	Water	GC-ECD	0.8	8						
94-82-6	DB;2,4-	615/8150	Waste/Groundwater	GC-ECD	0.91	9		5 - 9				
72-54-8	DDD;p,p'-	508	Drinking Water	GC-ECD	0.003	0.025			3.65E-1		5.04E-4	
72-54-8	DDD;p,p'-	625	Wastewater	GC/MS	2.8	28			3.65E-1		5.04E-4	
72-54-8	DDD;p,p'-	608/8150	Waste/Groundwater	GC-ECD	0.011	0.1		0.01 - 0.1	3.65E-1		5.04E-4	
72-55-9	DDE;p,p'-	625	Wastewater	GC/MS	5.6	56			2.57E-1		3.56E-4	
72-55-9	DDE;p,p'-	608/8150	Waste/Groundwater	GC-ECD	0.004	0.04		0.01 - 0.04	2.57E-1		3.56E-4	
72-55-9	DDE;p,p--	508	Drinking Water	GC-ECD	0.01	0.1			2.57E-1		3.56E-4	
50-29-3	DDT;p,p'-	508	Drinking Water	GC-ECD	0.06	0.6			2.57E-1		3.56E-4	
50-29-3	DDT;p,p'-	625	Wastewater	GC/MS	4.7	47			2.57E-1		3.56E-4	
50-29-3	DDT;p,p'-	608/8150	Waste/Groundwater	GC-ECD	0.012	0.1		0.01 - 0.1	2.57E-1		3.56E-4	
84-74-2	di-n-butyl phthalate	606	Wastewater	GC-FID	0.36	4						
117-84-0	di-n-octyl phthalate	606	Wastewater	GC-FID	3	30						
117-84-0	di-n-octyl phthalate	625	Wastewater	GC/MS	2.5	25						
117-84-0	di-n-octyl phthalate	8270	Groundwater	GC/MS		10		1 - 10				
2303-16-4	diallate	8150	Groundwater	GC-ECD		10		0.5 - 10	1.43E+0			
333-41-5	diazinon	614	Groundwater	GC-N/P	0.012	0.1						
333-41-5	diazinon	615/8140	Waste/Groundwater	GC-FPD	0.6	6		0.1 - 6				
53-70-3	dibenz[a,h]anthracene	625	Wastewater	GC/MS	2.5	25			1.20E-2		2.96E-2	
53-70-3	dibenz[a,h]anthracene	8270	Groundwater	GC/MS		10		3 - 10	1.20E-2		2.96E-2	
53-70-3	dibenz[a,h]anthracene	610/8310	Waste/Groundwater	HPLC	0.03	0.3		0.3 - 3	1.20E-2		2.96E-2	
132-64-9	dibenzofuran	8270	Groundwater	GC/MS		10		2 - 10				
124-48-1	dibromochloromethane (THM)	502.1	Drinking Water	GC-PID	0.008	0.08			5.21E-1		2.06E+1	
124-48-1	dibromochloromethane (THM)	502.2	Drinking Water	GC-ECD	0.03	0.3			5.21E-1		2.06E+1	
124-48-1	dibromochloromethane (THM)	524.1	Drinking Water	GC/MS	0.4	4			5.21E-1		2.06E+1	
124-48-1	dibromochloromethane (THM)	524.2	Drinking Water	GC/MS	0.05	0.5			5.21E-1		2.06E+1	
124-48-1	dibromochloromethane (THM)	601	Wastewater	GC-Hall	0.09	0.9			5.21E-1		2.06E+1	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
124-48-1	dibromochloromethane (THM)	624	Wastewater	GC/MS	3.1	31			5.21E-1		2.06E+1	
124-48-1	dibromochloromethane (THM)	8010	Groundwater	GC-Hall	0.9	9		0.2 - 10	5.21E-1		2.06E+1	
1918-00-9	dicamba	515.1	Water	GC-ECD	0.081	0.8						
1918-00-9	dicamba	615/8150	Groundwater	GC-ECD	0.27	3		0.5 - 3				
95-50-1	dichlorobenzene;1,2-	502.1	Drinking Water	GC-PID								
95-50-1	dichlorobenzene;1,2-	502.2	Drinking Water	GC-ECD	0.02	0.2						
95-50-1	dichlorobenzene;1,2-	503.1	Drinking Water	GC-ECD	0.02	0.2						
95-50-1	dichlorobenzene;1,2-	524.1	Drinking Water	GC/MS	1	10						
95-50-1	dichlorobenzene;1,2-	524.2	Drinking Water	GC/MS	0.03	0.3						
95-50-1	dichlorobenzene;1,2-	601	Wastewater	GC-Hall	0.15	2						
95-50-1	dichlorobenzene;1,2-	602	Wastewater	GC-PID	0.4	4						
95-50-1	dichlorobenzene;1,2-	624	Wastewater	GC/MS								
95-50-1	dichlorobenzene;1,2-	625	Wastewater	GC/MS	1.9	19						
95-50-1	dichlorobenzene;1,2-	8010	Groundwater	GC-Hall	0.15	2		1 - 100				
95-50-1	dichlorobenzene;1,2-	8020	Groundwater	GC-PID	0.4	4		0.5 - 4				
95-50-1	dichlorobenzene;1,2-	8270	Groundwater	GC/MS		10		1 - 100				
95-50-1	dichlorobenzene;1,2-	612/8120	Waste/Groundwater	GC-ECD	1.14	11		1 - 11				
541-73-1	dichlorobenzene;1,3-	502.1	Drinking Water	GC-PID					n/c		n/c	
541-73-1	dichlorobenzene;1,3-	502.2	Drinking Water	GC-ECD	0.02	0.2			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	503.1	Drinking Water	GC-ECD	0.006	0.06			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	524.1	Drinking Water	GC/MS					n/c		n/c	
541-73-1	dichlorobenzene;1,3-	524.2	Drinking Water	GC/MS	0.12	1			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	601	Wastewater	GC-Hall	0.32	3			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	602	Wastewater	GC-PID	0.4	4			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	624	Wastewater	GC/MS		3			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	625	Wastewater	GC/MS	1.9	19			n/c		n/c	
541-73-1	dichlorobenzene;1,3-	8010	Groundwater	GC-Hall	0.32	3		1 - 10	n/c		n/c	
541-73-1	dichlorobenzene;1,3-	8020	Groundwater	GC-PID	0.4	4		1 - 4	n/c		n/c	
541-73-1	dichlorobenzene;1,3-	8270	Groundwater	GC/MS		10		1 - 10	n/c		n/c	
541-73-1	dichlorobenzene;1,3-	612/8120	Waste/Groundwater	GC-ECD	1.19	12		0.5 - 12	n/c		n/c	
106-46-7	dichlorobenzene;1,4-	502.1	Drinking Water	GC-PID					1.82E+0		4.86E+0	
106-46-7	dichlorobenzene;1,4-	502.2	Drinking Water	GC-ECD	0.01	0.1			1.82E+0		4.86E+0	
106-46-7	dichlorobenzene;1,4-	503.1	Drinking Water	GC-ECD	0.006	0.06			1.82E+0		4.86E+0	
106-46-7	dichlorobenzene;1,4-	524.1	Drinking Water	GC/MS	2	20			1.82E+0		4.86E+0	
106-46-7	dichlorobenzene;1,4-	524.2	Drinking Water	GC/MS	0.03	0.3			1.82E+0		4.86E+0	
106-46-7	dichlorobenzene;1,4-	601	Wastewater	GC-Hall	0.24	2.4			1.82E+0		4.86E+0	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag = na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag = na)
106-46-7	dichlorobenzene;1,4-	602	Wastewater	GC-PID	0.3	3			1.82E+0	*	4.86E+0	
106-46-7	dichlorobenzene;1,4-	624	Wastewater	GC/MS					1.82E+0		4.86E+0	
106-46-7	dichlorobenzene;1,4-	625	Wastewater	GC/MS	4.4	44			1.82E+0	*	4.86E+0	*
106-46-7	dichlorobenzene;1,4-	8010	Groundwater	GC-Hall	0.24	2		1 - 10	1.82E+0	*	4.86E+0	
106-46-7	dichlorobenzene;1,4-	8020	Groundwater	GC-PID	0.3	3		0.5 - 10	1.82E+0	*	4.86E+0	
106-46-7	dichlorobenzene;1,4-	8270	Groundwater	GC/MS		10		1 - 10	1.82E+0	*	4.86E+0	*
106-46-7	dichlorobenzene;1,4-	612/8120	Waste/Groundwater	GC-ECD	1.34	13		0.5 - 13	1.82E+0	*	4.86E+0	*
91-94-1	dichlorobenzidine;3,3-	605	Wastewater	HPLC	0.13	1			1.94E-1	*	4.62E-2	*
91-94-1	dichlorobenzidine;3,3-	625	Wastewater	GC/MS	16.5	165			1.94E-1	*	4.62E-2	*
91-94-1	dichlorobenzidine;3,3-	8270	Groundwater	GC/MS		20		2 - 20	1.94E-1	*	4.62E-2	*
75-71-8	dichlorodifluoromethane	502.1	Drinking Water	GC-PID								
75-71-8	dichlorodifluoromethane	502.2	Drinking Water	GC-ECD	0.05	0.5						
75-71-8	dichlorodifluoromethane	524.1	Drinking Water	GC/MS	0.3	3						
75-71-8	dichlorodifluoromethane	524.2	Drinking Water	GC/MS	0.1	1						
75-71-8	dichlorodifluoromethane	601	Wastewater	GC-Hall	1.81	18						
75-71-8	dichlorodifluoromethane	8240	Groundwater	GC/MS		5		0.2 - 20				
75-34-3	dichloroethane;1,1-	502.1	Drinking Water	GC-PID	0.003	0.03						
75-34-3	dichloroethane;1,1-	502.2	Drinking Water	GC-ECD	0.07	0.7						
75-34-3	dichloroethane;1,1-	524.1	Drinking Water	GC/MS	0.2	2						
75-34-3	dichloroethane;1,1-	524.2	Drinking Water	GC/MS	0.04	0.4						
75-34-3	dichloroethane;1,1-	601	Wastewater	GC-Hall	0.07	0.7						
75-34-3	dichloroethane;1,1-	624	Wastewater	GC/MS	4.7	47						
75-34-3	dichloroethane;1,1-	8010	Groundwater	GC-Hall	0.07	0.7						
75-34-3	dichloroethane;1,1-	8240	Groundwater	GC/MS		5		0.2 - 10				
107-06-2	dichloroethane;1,2-	502.1	Drinking Water	GC-PID	0.002	0.02			4.81E-1		5.94E+1	
107-06-2	dichloroethane;1,2-	502.2	Drinking Water	GC-ECD	0.03	0.3			4.81E-1		5.94E+1	
107-06-2	dichloroethane;1,2-	524.1	Drinking Water	GC/MS	0.2	2			4.81E-1	*	5.94E+1	
107-06-2	dichloroethane;1,2-	524.2	Drinking Water	GC/MS	0.06	0.6			4.81E-1	*	5.94E+1	
107-06-2	dichloroethane;1,2-	601	Wastewater	GC-Hall	0.03	0.3			4.81E-1		5.94E+1	
107-06-2	dichloroethane;1,2-	624	Wastewater	GC/MS	2.8	28			4.81E-1	*	5.94E+1	
107-06-2	dichloroethane;1,2-	8010	Groundwater	GC-Hall	0.03	0.3		0.3 - 2	4.81E-1		5.94E+1	
107-06-2	dichloroethane;1,2-	8240	Groundwater	GC/MS		5		0.2 - 10	4.81E-1	*	5.94E+1	
75-35-4	dichloroethene;1,1-	502.1	Drinking Water	GC-PID	0.003	0.03			7.29E-2		1.93E+0	
75-35-4	dichloroethene;1,1-	502.2	Drinking Water	GC-ECD	0.07	0.7			7.29E-2	*	1.93E+0	
75-35-4	dichloroethene;1,1-	524.1	Drinking Water	GC/MS	0.2	2			7.29E-2	*	1.93E+0	*
75-35-4	dichloroethene;1,1-	524.2	Drinking Water	GC/MS	0.12	1			7.29E-2	*	1.93E+0	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
75-35-4	dichloroethene;1,1-	601	Wastewater	GC-Hall	0.13	1			7.29E-2		1.93E+0	
75-35-4	dichloroethene;1,1-	624	Wastewater	GC/MS	2.8	28			7.29E-2		1.93E+0	
75-35-4	dichloroethene;1,1-	8010	Groundwater	GC-Hall	0.13	1		0.2 - 10	7.29E-2		1.93E+0	
75-35-4	dichloroethene;1,1-	8240	Groundwater	GC/MS		5		1 - 10	7.29E-2		1.93E+0	
156-59-2	dichloroethylene; 1,2-cis-	502.1	Drinking Water	GC-PID	0.002	0.02						
156-59-2	dichloroethylene; 1,2-cis-	502.2	Drinking Water	GC-ECD	0.01	0.1						
156-59-2	dichloroethylene; 1,2-cis-	524.1	Drinking Water	GC/MS								
156-59-2	dichloroethylene; 1,2-cis-	524.2	Drinking Water	GC/MS	0.12	1						
156-59-2	dichloroethylene; 1,2-cis-	601	Wastewater	GC-Hall	0.1	1						
156-59-2	dichloroethylene; 1,2-cis-	624	Wastewater	GC/MS	1.6	16						
156-59-2	dichloroethylene; 1,2-cis-	8010	Groundwater	GC-Hall	0.1	1		0.2 - 10				
156-59-2	dichloroethylene; 1,2-cis-	8240	Groundwater	GC/MS		5		0.2 - 10				
156-60-5	dichloroethylene; 1,2-trans-	502.1	Drinking Water	GC-PID	0.002	0.02						
156-60-5	dichloroethylene; 1,2-trans-	502.2	Drinking Water	GC-ECD	0.06	0.6						
156-60-5	dichloroethylene; 1,2-trans-	524.1	Drinking Water	GC/MS	0.2	2						
156-60-5	dichloroethylene; 1,2-trans-	524.2	Drinking Water	GC/MS	0.06	0.6						
156-60-5	dichloroethylene; 1,2-trans-	601	Wastewater	GC-Hall	0.1	1						
156-60-5	dichloroethylene; 1,2-trans-	624	Wastewater	GC/MS	1.6	16						
156-60-5	dichloroethylene; 1,2-trans-	8010	Groundwater	GC-Hall	0.1	1		0.2 - 10				
156-60-5	dichloroethylene; 1,2-trans-	8240	Groundwater	GC/MS		5		0.2 - 10				
	dichloroethylene;1,2- (total)	502.1	Drinking Water	GC-PID	0.002	0.02			n/c		n/c	
	dichloroethylene;1,2- (total)	502.2	Drinking Water	GC-ECD	0.06	0.6			n/c		n/c	
	dichloroethylene;1,2- (total)	524.1	Drinking Water	GC/MS	0.2	2			n/c		n/c	
	dichloroethylene;1,2- (total)	524.2	Drinking Water	GC/MS	0.12	1			n/c		n/c	
	dichloroethylene;1,2- (total)	601	Wastewater	GC-Hall	0.1	1			n/c		n/c	
	dichloroethylene;1,2- (total)	624	Wastewater	GC/MS	1.6	16			n/c		n/c	
	dichloroethylene;1,2- (total)	8010	Groundwater	GC-Hall	0.1	1		0.2 - 10	n/c		n/c	
	dichloroethylene;1,2- (total)	8240	Groundwater	GC/MS		5		0.2 - 10	n/c		n/c	
120-83-2	dichlorophenol;2,4-	625	Wastewater	GC/MS	2.7	27		2 - 27				
120-83-2	dichlorophenol;2,4-	8270	Groundwater	GC/MS		10		1 - 10				
120-83-2	dichlorophenol;2,4-	604/8040	Waste/Groundwater	GC-FID	0.39	4		1 - 4				
120-83-2	dichlorophenol;2,4-			GC-ECD	0.68	7		0.07 - 10				
94-75-7	dichlorophenoxyacetic acid;2,4- (	515.1	Water	GC-ECD	0.2	2						
94-75-7	dichlorophenoxyacetic acid;2,4- (	615/8150	Waste/Groundwater	GC-ECD	1.2	12		0.5 - 12				
78-87-5	dichloropropane;1,2-	502.1	Drinking Water	GC-PID					6.43E-1		2.32E+1	
78-87-5	dichloropropane;1,2-	502.2	Drinking Water	GC-ECD	0.01	0.1			6.43E-1		2.32E+1	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
78-87-5	dichloropropane;1,2-	524.1	Drinking Water	GC/MS	0.2	2			6.43E-1		2.32E+1	
78-87-5	dichloropropane;1,2-	524.2	Drinking Water	GC/MS	0.04	0.4			6.43E-1		2.32E+1	
78-87-5	dichloropropane;1,2-	601	Wastewater	GC-Hall	0.04	0.4			6.43E-1		2.32E+1	
78-87-5	dichloropropane;1,2-	624	Wastewater	GC/MS		5		1 - 10	6.43E-1		2.32E+1	
78-87-5	dichloropropane;1,2-	8010	Groundwater	GC-Hall	0.04	0.4		0.4 - 2	6.43E-1		2.32E+1	
78-87-5	dichloropropane;1,2-	8240	Groundwater	GC/MS		5		1 - 10	6.43E-1		2.32E+1	
542-75-6	dichloropropene;1,3- (total)	601	Wastewater	GC-Hall	0.2	2			2.43E-1		1.89E+1	
542-75-6	dichloropropene;1,3- (total)	624	Wastewater	GC/MS		5		0.2 - 10	2.43E-1		1.89E+1	
	dichloropropene;1,3-cis-	601	Wastewater	GC-Hall	0.2	2			n/c		n/c	
	dichloropropene;1,3-cis-	624	Wastewater	GC/MS					n/c		n/c	
	dichloropropene;1,3-cis-	8240	Groundwater	GC/MS		5		0.2 - 10	n/c		n/c	
	dichloropropene;1,3-trans-	601	Wastewater	GC-Hall	0.34	3			n/c		n/c	
	dichloropropene;1,3-trans-	624	Wastewater	GC/MS	5	50			n/c		n/c	
	dichloropropene;1,3-trans-	8240	Groundwater	GC/MS		5		0.2 - 10	n/c		n/c	
60-57-1	dieldrin	505	Drinking Water	GC-ECD	0.012	0.1			5.47E-3		8.67E-5	
60-57-1	dieldrin	625	Wastewater	GC/MS	2.5	25			5.47E-3		8.67E-5	
60-57-1	dieldrin	608/8080	Waste/Groundwater	GC-ECD	0.002	0.02		0.01 - 0.02	5.47E-3		8.67E-5	
84-66-2	diethyl phthalate	625	Wastewater	GC/MS	22	22						
84-66-2	diethyl phthalate	8060	Groundwater	GC-FID	31	310		51 - 310				
84-66-2	diethyl phthalate	8270	Groundwater	GC/MS		10		0.6 - 10				
84-66-2	diethyl phthalate	608/8060	Waste/Groundwater	GC-ECD	0.49	5		2 - 10				
	dimethoxybenzidine;3,3'-	8270	Groundwater	GC/MS		100		2 - 100	n/c		n/c	
131-11-3	dimethyl phthalate	625	Wastewater	GC/MS	1.6	16						
131-11-3	dimethyl phthalate	8060	Groundwater	GC-FID	19	190		0.6 - 190				
131-11-3	dimethyl phthalate	8270	Groundwater	GC/MS		10		0.6 - 10				
131-11-3	dimethyl phthalate	608/8060	Waste/Groundwater	GC-ECD	0.29	3		0.3 - 10				
119-93-7	dimethylbenzidine;3,3'-	8270	Groundwater	GC/MS		10		1 - 10	9.51E-3			
540-73-8	dimethylhydrazine;1,2-			HPLC-UV					6.25E-5			
105-67-9	dimethylphenol;2,4-	625	Wastewater	GC/MS	2.7	27		2 - 27				
105-67-9	dimethylphenol;2,4-	8270	Groundwater	GC/MS		10		1 - 10				
105-67-9	dimethylphenol;2,4-	604/8040	Waste/Groundwater	GC-FID	0.32	3		2 - 6				
105-67-9	dimethylphenol;2,4-			GC-ECD	0.63	6		6 - 10				
534-52-1	dinitro-o-cresol;4,6-	8270	Groundwater	GC/MS		50		4 - 50	n/c		n/c	
51-28-5	dinitrophenol;2,4-	625	Wastewater	GC/MS	42	420		2 - 420				
51-28-5	dinitrophenol;2,4-	8270	Groundwater	GC/MS		50		2 - 50				
51-28-5	dinitrophenol;2,4-	604/8040	Waste/Groundwater	GC-FID	13	130		4 - 130				

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
121-14-2	dinitrotoluene;2,4-	625	Wastewater	GC/MS	5.7	57						
121-14-2	dinitrotoluene;2,4-	8270	Groundwater	GC/MS		10		0.8 - 10				
121-14-2	dinitrotoluene;2,4-	609/8090	Waste/Groundwater	GC-ECD	0.02	0.2		0.01 - 0.2				
606-20-2	dinitrotoluene;2,6-	625	Wastewater	GC/MS	1.9	19						
606-20-2	dinitrotoluene;2,6-	8270	Groundwater	GC/MS		10		0.8 - 10				
606-20-2	dinitrotoluene;2,6-	609/8090	Waste/Groundwater	GC-ECD	0.01	0.1		0.1 - 10				
88-85-1	dinoseb	515.1	Water	GC-ECD	0.19	2						
88-85-1	dinoseb	8270	Groundwater	GC/MS		20		0.5 - 20				
88-85-1	dinoseb	615/8150	Waste/Groundwater	GC-ECD	0.07	0.7		0.5 - 7				
123-91-1	dioxane;1,4-	8240	Groundwater	GC/MS		10		2 - 10	7.95E+0			
122-66-7	diphenylhydrazine;1,2-	8240	Groundwater	GC/MS		20		4 - 20	1.09E-1		3.25E-1	
298-04-4	disulfoton	507	Drinking Water	GC-N/P	0.3	3						
298-04-4	disulfoton	614	Wastewater	GC-FPD								
298-04-4	disulfoton	622	Wastewater	GC-N/P	0.2	2						
298-04-4	disulfoton	8140	Groundwater	GC-FPD	0.2	2		0.1 - 2				
298-04-4	disulfoton	8270	Groundwater	GC/MS		10		1 - 10				
	endosulfan (alpha, beta)	508	Drinking Water	GC-ECD					n/c		n/c	
	endosulfan (alpha, beta)	625	Wastewater	GC/MS					n/c		n/c	
	endosulfan (alpha, beta)	608/8080	Waste/Groundwater	GC-ECD					n/c		n/c	
	endosulfan I	508	Drinking Water	GC-ECD	0.015	0.2			n/c	⚑	n/c	⚑
	endosulfan I	625	Wastewater	GC/MS					n/c		n/c	
	endosulfan I	608/8080	Waste/Groundwater	GC-ECD	0.014	0.1		0.005 - 0.1	n/c	⚑	n/c	⚑
	endosulfan II	508	Drinking Water	GC-ECD	0.024	0.2			n/c	⚑	n/c	⚑
	endosulfan II	625	Wastewater	GC/MS					n/c		n/c	
	endosulfan II	608/8080	Waste/Groundwater	GC-ECD	0.004	0.04		0.01 - 0.1	n/c	⚑	n/c	⚑
1031-07-8	endosulfan sulfate	508	Drinking Water	GC-ECD	0.015	0.2			n/c	⚑	n/c	⚑
1031-07-8	endosulfan sulfate	625	Wastewater	GC/MS	5.6	56			n/c	⚑	n/c	⚑
1031-07-8	endosulfan sulfate	608/8080	Waste/Groundwater	GC-ECD	0.066	0.7		0.01 - 0.7	n/c	⚑	n/c	⚑
145-73-3	endothall	Penwalt	Groundwater	Color								
72-20-8	endrin	505	Drinking Water	GC-ECD	0.063	0.63						
72-20-8	endrin	508	Drinking Water	GC-ECD	0.015	0.2						
72-20-8	endrin	608/8080	Waste/Groundwater	GC-ECD	0.006	0.06		0.01 - 0.1				
53494-70-5	endrin ketone	8080	Groundwater	GC-ECD					n/c		n/c	
106-89-8	epichlorohydrin	8080	Groundwater	GC-ECD					8.84E+0			
140-88-5	ethyl acrylate	8020	Wastewater	GC-PID		10		1 - 10	1.82E+0			
100-41-4	ethylbenzene	502.1	Drinking Water	GC-PID	0.01	0.1						

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
100-41-4	ethylbenzene	502.2	Drinking Water	GC								
100-41-4	ethylbenzene	503.1	Drinking Water	GC	0.002	0.02						
100-41-4	ethylbenzene	524.1	Drinking Water	GC/MS	0.06	0.6						
100-41-4	ethylbenzene	524.2	Drinking Water	GC/MS	0.2	2						
100-41-4	ethylbenzene	601	Wastewater	GC	7.2	72						
100-41-4	ethylbenzene	624	Wastewater	GC/MS	7.2	72						
100-41-4	ethylbenzene	8240	Groundwater	GC/MS		5		0.5 - 10				
106-93-4	ethylene dibromide (EDB)	504	Drink/Groundwater	GC	0.01	0.1			5.15E-4			
106-93-4	ethylene dibromide (EDB)	EPA 1985	Wastewater	GC-ECD	0.2	2			5.15E-4			
107-21-1	ethylene glycol		Groundwater	GC-FID		1000		2 - 1000				
96-45-7	ethylene thiourea	632	Wastewater	HPLC					2.43E+0			
206-44-0	fluoranthene	625	Wastewater	GC/MS	2.2	22						
206-44-0	fluoranthene	8270	Groundwater	GC/MS		10		1.2 - 10				
206-44-0	fluoranthene	610/8310	Waste/Groundwater	HPLC	0.21	2		1.2 - 2				
86-73-7	fluorene	625	Wastewater	GC/MS	1.9	19		1 - 19				
86-73-7	fluorene	8270	Groundwater	GC/MS		10		1 - 10				
86-73-7	fluorene	610/8310	Waste/Groundwater	HPLC	0.21	2		1 - 2				
133-07-3	folpet								2.50E+1			
67-45-8	furazolidone								2.30E-2			
531-82-8	furium								1.75E-3			
76-44-8	heptachlor	505	Drinking Water	GC-ECD	0.003	0.03		0.005 - 0.03	1.94E-2		1.29E-4	
76-44-8	heptachlor	508	Drinking Water	GC-ECD	0.01	0.1			1.94E-2		1.29E-4	
76-44-8	heptachlor	625	Wastewater	GC/MS	1.9	19			1.94E-2		1.29E-4	
76-44-8	heptachlor	608/8080	Waste/Groundwater	GC-ECD	0.003	0.03		0.005 - 0.03	1.94E-2		1.29E-4	
1024-57-3	heptachlor epoxide	505	Drinking Water	GC-ECD	0.004	0.04			9.62E-3		6.36E-5	
1024-57-3	heptachlor epoxide	508	Drinking Water	GC-ECD	0.015	0.2			9.62E-3		6.36E-5	
1024-57-3	heptachlor epoxide	625	Wastewater	GC/MS	2.2	22			9.62E-3		6.36E-5	
1024-57-3	heptachlor epoxide	608/8080	Waste/Groundwater	GC-ECD	0.083	0.8		0.005 - 0.8	9.62E-3		6.36E-5	
118-74-1	hexachlorobenzene	505	Drinking Water	GC-ECD	0.002	0.02			5.47E-2		4.66E-4	
118-74-1	hexachlorobenzene	508	Drinking Water	GC-ECD	0.008	0.08			5.47E-2		4.66E-4	
118-74-1	hexachlorobenzene	625	Wastewater	GC/MS	1.9	19			5.47E-2		4.66E-4	
118-74-1	hexachlorobenzene	8270	Groundwater	GC/MS		10		1 - 10	5.47E-2		4.66E-4	
118-74-1	hexachlorobenzene	612/8120	Waste/Groundwater	GC-ECD	0.05	0.5		0.5 - 10	5.47E-2		4.66E-4	
87-68-3	hexachlorobutadiene	524.2	Drinking Water	GC/MS	0.11	1			5.61E-1		2.99E+1	
87-68-3	hexachlorobutadiene	625	Wastewater	GC/MS	0.9	9			5.61E-1		2.99E+1	
87-68-3	hexachlorobutadiene	8270	Groundwater	GC/MS		10		2 - 10	5.61E-1		2.99E+1	

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
87-68-3	hexachlorobutadiene	502.2/503.1	Drinking Water	GC-ECD	0.02	0.2			5.61E-1		2.99E+1	
87-68-3	hexachlorobutadiene	612/8120	Waste/Groundwater	GC-ECD	0.34	3		1 - 10	5.61E-1	*	2.99E+1	
319-84-6	hexachlorocyclohexane;alpha	608/8080	Waste/Groundwater	GC-ECD	0.003	0.03		0.005 - 0.03	1.39E-2	*	7.91E-3	*
319-85-7	hexachlorocyclohexane;beta	608/8080	Waste/Groundwater	GC-ECD	0.006	0.06		0.005 - 0.06	4.86E-2	*	2.77E-2	*
319-86-8	hexachlorocyclohexane;delta	608/8080	Waste/Groundwater	GC-ECD	0.009	0.09		0.005 - 0.09				
58-89-9	hexachlorocyclohexane;gamma (li	505	Drinking Water	GC-ECD	0.003	0.03		0.005 - 0.1	6.73E-2		3.84E-2	
58-89-9	hexachlorocyclohexane;gamma (li	8080	Groundwater	GC-ECD	0.004	0.04		0.005 - 0.1	6.73E-2		3.84E-2	*
77-47-4	hexachlorocyclopentadiene	505	Drinking Water	GC-ECD	0.13	1						
77-47-4	hexachlorocyclopentadiene	8120	Groundwater	GC-ECD	0.4	4		4 - 10				
77-47-4	hexachlorocyclopentadiene	8270	Groundwater	GC/MS		10		1 - 10				
67-72-1	hexachloroethane	625	Wastewater	GC/MS	1.6	16			6.25E+0	*	5.33E+0	*
67-72-1	hexachloroethane	8270	Groundwater	GC/MS		10		1 - 10	6.25E+0	*	5.33E+0	*
67-72-1	hexachloroethane	612/8120	Waste/Groundwater	GC-ECD	0.03	0.3		0.3 - 10	6.25E+0		5.33E+0	
591-78-6	hexanone;2-	8240	Groundwater	GC/MS		50		1 - 50	n/c	⚑	n/c	⚑
302-01-2	hydrazine sulfate	8270	Groundwater	GC/MS		50		0.05 - 50	2.92E-2	*		
193-39-5	indeno[1,2,3-c,d]pyrene	625	Wastewater	GC/MS	3.7	37			1.20E-2	*	2.96E-2	*
193-39-5	indeno[1,2,3-c,d]pyrene	8270	Groundwater	GC/MS		10		2 - 10	1.20E-2	*	2.96E-2	*
193-39-5	indeno[1,2,3-c,d]pyrene	610/8310	Waste/Groundwater	HPLC	0.043	0.4		0.4 - 2	1.20E-2	*	2.96E-2	*
78-59-1	isophorone	625	Wastewater	GC/MS	2.2	22			9.21E+1		1.56E+3	
78-59-1	isophorone	8090	Groundwater	GC-FID	5.7	57		2 - 57	9.21E+1		1.56E+3	
78-59-1	isophorone	8270	Groundwater	GC/MS		10		2 - 10	9.21E+1		1.56E+3	
78-59-1	isophorone	609/8090	Waste/Groundwater	GC-ECD	15.7	157		10 - 160	9.21E+1	*	1.56E+3	
7439-92-1	lead	200.7	Water	ICP	42	420		5 - 50				
7439-92-1	lead	200.7/6010	Groundwater	ICP	42	420						
7439-92-1	lead	239.1/7420	Water	FAA	100	1000						
7439-92-1	lead	239.2/7421	Water	GFAA	1	10						
121-75-5	malathion	614	Wastewater	GC-FPD	ND							
121-75-5	malathion	8270	Groundwater	GC/MS		50		1 - 50				
7439-97-6	mercury (inorganic)	7471	Groundwater	AA	0.2	2						
7439-97-6	mercury (inorganic)	245.1/7470	Water/Groundwater	AA	0.2	2		0.001 - 2				
72-43-5	methoxychlor	505	Drinking Water	GC-ECD	0.96	10						
72-43-5	methoxychlor	8080	Groundwater	GC-ECD	0.176	2		0.02 - 2				
72-43-5	methoxychlor	8270	Groundwater	GC/MS		10		1 - 10				
74-83-9	methyl bromide	8011	Groundwater	GC/ECD		10		1 - 10				
78-93-3	methyl ethyl ketone (MEK)	8015	Groundwater	GC-FID								
108-10-1	methyl isobutyl ketone (MIBK)	8015	Groundwater	GC-FID								

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
298-00-0	methyl parathion	8140	Groundwater	GC-FID	0.03	0.3		0.25 - 0.3				
298-00-0	methyl parathion	8270	Groundwater	GC/MS		10		0.3 - 10				
94-74-6	methyl-4-chlorophenoxy-acetic acl	615/8150	Waste/Groundwater	GC-ECD	249	2500		250 - 2500				
636-21-5	methylanaline hydrochloride;2-	8270	Groundwater	GC/MS		10		1 - 10	4.86E-1			
95-53-4	methylanaline;2-	8270	Groundwater	GC/MS		10		1 - 10	3.65E-1			
75-09-2	methylene chloride	502.1	Drinking Water	GC-PID					5.83E+0		9.60E+2	
75-09-2	methylene chloride	502.2	Drinking Water	GC-ECD	0.02	0.2			5.83E+0		9.60E+2	
75-09-2	methylene chloride	524.1	Drinking Water	GC/MS	1	10			5.83E+0		9.60E+2	
75-09-2	methylene chloride	524.2	Drinking Water	GC/MS	0.03	0.3			5.83E+0		9.60E+2	
75-09-2	methylene chloride	601	Wastewater	GC-Hall	0.25	3			5.83E+0		9.60E+2	
75-09-2	methylene chloride	624	Wastewater	GC/MS	2.8	28			5.83E+0		9.60E+2	
75-09-2	methylene chloride	8010	Groundwater	GC-Hall					5.83E+0		9.60E+2	
75-09-2	methylene chloride	8240	Groundwater	GC/MS		5		0.2 - 10	5.83E+0		9.60E+2	
	methylnaphthalene;2-	8270	Groundwater	GC/MS		10		3 - 10	n/c		n/c	
2385-85-5	mirex	617	Wastewater	GC-ECD	0.015	0.2			4.86E-2			
2385-85-5	mirex	8270	Groundwater	GC/MS		10		0.1 - 10	4.86E-2			
91-20-3	naphthalene	502.2	Drinking Water	GC-PID	0.06	0.6						
91-20-3	naphthalene	503.1	Drinking Water	GC-PID	0.04	0.4						
91-20-3	naphthalene	524.2	Drinking Water	GC/MS	0.04	0.4						
91-20-3	naphthalene	625	Wastewater	GC/MS	1.6	16		3 - 16				
91-20-3	naphthalene	8100	Groundwater	GC-FID								
91-20-3	naphthalene	8270	Groundwater	GC/MS		10		3 - 10				
91-20-3	naphthalene	610/8310	Waste/Groundwater	HPLC	1.8	18		3 - 18				
unavailable03	nickel, refinery dust NOTE: Meth	249.2	Water	GFAA	1	10						
unavailable03	nickel, refinery dust NOTE: Meth	200.7/6010	Groundwater	ICP	15	150		10 - 150				
unavailable03	nickel, refinery dust NOTE: Meth	249.1/7520	Surface Water	FAA	40	400						
7440-02-0	nickel, sol. salts NOTE: Method	249.2	Water	GFAA	1	10						
7440-02-0	nickel, sol. salts NOTE: Method	200.7/6010	Groundwater	ICP	15	150		10 - 150				
7440-02-0	nickel, sol. salts NOTE: Method	249.1/7520	Surface Water	FAA	40	400						
88-74-4	nitroaniline;2-	8270	Groundwater	GC/MS		50		6 - 50	n/c		n/c	
99-09-2	nitroaniline;3-	8270	Groundwater	GC/MS		50		6 - 50	n/c		n/c	
100-01-6	nitroaniline;4-	8270	Groundwater	GC/MS		20		2 - 50	n/c		n/c	
98-95-3	nitrobenzene	625	Wastewater	GC/MS	1.9	19						
98-95-3	nitrobenzene	8090	Groundwater	GC-FID	3.6	36		10 - 36				
98-95-3	nitrobenzene	8270	Groundwater	GC/MS		10		2 - 10				
98-95-3	nitrobenzene	609/8090	Waste/Groundwater	GC-ECD	13.7	140		10 - 140				

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
59-87-0	nitrofurazone								5.83E-2			
	nitrophenol;2-	625	Wastewater	GC/MS	3.6	36		2 - 36	n/c		n/c	
	nitrophenol;2-	8040	Groundwater	GC-FID	0.45	5		5 - 10	n/c		n/c	
	nitrophenol;2-	8270	Groundwater	GC/MS		10		2 - 10	n/c		n/c	
	nitrophenol;2-	604/8040	Waste/Groundwater	GC-ECD	0.77	8		2 - 8	n/c		n/c	
	nitrophenol;4	625	Wastewater	GC/MS	2.4	24		4 - 24	n/c		n/c	
	nitrophenol;4-	515.1	Water	GC-ECD	0.13	1			n/c		n/c	
	nitrophenol;4-	8270	Groundwater	GC/MS		50		4 - 50	n/c		n/c	
	nitrophenol;4-	604/8040	Waste/Groundwater	GC-FID	2.8	28		4 - 28	n/c		n/c	
	nitrophenol;4-	8040	Groundwater	GC-ECD	0.7	7		1 - 7	n/c		n/c	
924-16-3	nitroso-di-n-butylamine;N-	607	Wastewater	GC-Hall		10		1 - 10	1.62E-2			
924-16-3	nitroso-di-n-butylamine;N-	8270	Groundwater	GC/MS		10		1 - 10	1.62E-2			
621-64-7	nitroso-di-n-propylamine;N-	607	Wastewater	GC-NP/Hall	0.46	5			1.25E-2		8.19E-1	
621-64-7	nitroso-di-n-propylamine;N-	8270	Groundwater	GC/MS		10		2 - 10	1.25E-2		8.19E-1	
1116-54-7	nitrosodiethanolamine;N-	607/8270	Waste/Groundwater	GC-Hall/GC-MS		10		1 - 10	3.13E-2			
55-18-5	nitrosodiethylamine;N-	607	Wastewater	GC-Hall		10		1 - 10	5.83E-4			
55-18-5	nitrosodiethylamine;N-	8270	Groundwater	GC/MS		20		6 - 20	5.83E-4			
62-75-9	nitrosodimethylamine;N- (DMNA)	607	Wastewater	GC-NP/GC-Hall	0.15	2			1.72E-3		4.89E+0	
86-30-6	nitrosodiphenylamine;N-	607	Wastewater	GC-NP/GC-Hall	0.81	8			1.79E+1		9.73E+0	
86-30-6	nitrosodiphenylamine;N-	625	Wastewater	GC/MS	1.9	19			1.79E+1		9.73E+0	
86-30-6	nitrosodiphenylamine;N-	8270	Groundwater	GC/MS		10		2 - 10	1.79E+1		9.73E+0	
10595-95-6	nitrosomethylethylamine;N-	625	Wastewater	GC/MS					3.98E-3			
930-55-2	nitrosopyrrolidine;N-	607	Wastewater	GC-Hall		10		1 - 10	4.17E-2			
930-55-2	nitrosopyrrolidine;N-	8270	Groundwater	GC/MS		40		10 - 40	4.17E-2			
56-38-2	parathion	614	Wastewater	GC-NP		6		0.3 - 6				
56-38-2	parathion	8270	Groundwater	GC/MS		10		0.3 - 10				
608-93-5	pentachlorobenzene	8270	Groundwater	GC/MS		10		1 - 10				
87-86-5	pentachlorophenol (PCP)	515.1	Water	GC-ECD	0.076	0.8			7.29E-1		4.91E+0	
87-86-5	pentachlorophenol (PCP)	625	Wastewater	GC/MS	3.6	36		2 - 50	7.29E-1		4.91E+0	
87-86-5	pentachlorophenol (PCP)	8040	Groundwater	GC-FID	7.4	74		30 - 74	7.29E-1		4.91E+0	
87-86-5	pentachlorophenol (PCP)	8270	Groundwater	GC/MS		50		4 - 50	7.29E-1		4.91E+0	
87-86-5	pentachlorophenol (PCP)		Groundwater	GC-ECD	0.59	6		1 - 6	7.29E-1		4.91E+0	
85-01-8	phenanthrene	625	Wastewater	GC/MS	5.4	54		1 - 54	n/c		n/c	
85-01-8	phenanthrene	8270	Groundwater	GC/MS		10		1 - 10	n/c		n/c	
85-01-8	phenanthrene	610/8310	Waste/Groundwater	HPLC	0.64	6		6 - 10	n/c		n/c	
108-95-2	phenol	625	Wastewater	GC/MS	1.5	15		6 - 15				

n/c = not calculated

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TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
108-95-2	phenol	8270	Groundwater	GC/MS		10		6 - 10				
108-95-2	phenol	604/8040	Waste/Groundwater	GC-FID	0.14	1		0.5 - 1				
93-65-2	propionic acid;2(2-methyl)-4-chlor	615/8150	Waste/Groundwater	GC-ECD	192	1900		250 - 2500				
129-00-0	pyrene	625	Wastewater	GC/MS	1.9	19						
129-00-0	pyrene	8270	Groundwater	GC/MS		10		1 - 10				
129-00-0	pyrene	610/8310	Waste/Groundwater	HPLC	0.27	3		1 - 3				
7782-49-2	selenium	200.7/6010	Groundwater	ICP	75	750		5 - 750				
7782-49-2	selenium	270.2/7740	Groundwater	GFAA	2	20						
7782-49-2	selenium	270.3/7741	Groundwater	GHAA	2	20						
7440-22-4	silver	200.7/6010	Groundwater	ICP	7	70		0.5 - 20				
7440-22-4	silver	272.1/7740	Groundwater	FAA	10	100						
7440-22-4	silver	272.2/7741	Groundwater	GFAA	0.2	2						
122-34-9	simazine	507	Drinking Water	GC-N/P	0.075	0.75		0.3 - 10	7.29E-1			
122-34-9	simazine	619	Wastewater	GC-Hall	0.06	0.6			7.29E-1			
100-42-5	styrene	502.2	Drinking Water	GC-PID	0.01	0.1			1.46E+0			
100-42-5	styrene	503.1	Drinking Water	GC-PID	0.008	0.08			1.46E+0			
100-42-5	styrene	524.1	Drinking Water	GC/MS	0.2	2			1.46E+0			
100-42-5	styrene	524.2	Drinking Water	GC/MS	0.04	0.4			1.46E+0			
100-42-5	styrene	8240	Groundwater	GC/MS		5		1 - 10	1.46E+0			
1746-01-6	TCDD;2,3,7,8- (dioxin)	8290	Groundwater	HRGC/HRMS	3E-04	0.003			5.83E-7		8.64E-9	
	TCDF;2,3,7,8-	8290	Groundwater	HRGC/HRMS	3E-04	0.003			n/c		n/c	
95-94-3	tetrachlorobenzene;1,2,4,5-	8270	Groundwater	GC/MS		10		1 - 10				
79-34-5	tetrachloroethane;1,1,2,2-	502.1	Drinking Water	GC-Hall	0.01	0.1			2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	502.2	Drinking Water	GC-ECD	0.01	0.1			2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	524.1	Drinking Water	GC/MS	0.4	4			2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	524.2	Drinking Water	GC/MS	0.05	0.5			2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	601	Wastewater	GC/MS	0.03	0.3			2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	624	Wastewater	GC/MS	6.9	69			2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	8010	Groundwater	GC-Hall	0.03	0.3		0.3 - 2	2.19E-1		6.48E+0	
79-34-5	tetrachloroethane;1,1,2,2-	8240	Groundwater	GC/MS		5		0.2 - 10	2.19E-1		6.48E+0	
127-18-4	tetrachloroethylene (PCE)	502.1	Drinking Water	GC-Hall	0.001	0.01			8.58E-1		4.15E+0	
127-18-4	tetrachloroethylene (PCE)	502.2	Drinking Water	GC-ECD	0.04	0.4			8.58E-1		4.15E+0	
127-18-4	tetrachloroethylene (PCE)	503.1	Drinking Water	GC-PID	0.01	0.1			8.58E-1		4.15E+0	
127-18-4	tetrachloroethylene (PCE)	524.1	Drinking Water	GC/MS	0.3	3			8.58E-1		4.15E+0	
127-18-4	tetrachloroethylene (PCE)	524.2	Drinking Water	GC/MS	0.14	1			8.58E-1		4.15E+0	
127-18-4	tetrachloroethylene (PCE)	601	Wastewater	GC-Hall	0.03	0.3			8.58E-1		4.15E+0	

n/c = not calculated

pqlh2o.xls

TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

♣ Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)	♣	LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
127-18-4	tetrachloroethylene (PCE)	624	Wastewater	GC/MS	4.1	41			8.58E-1	♣	4.15E+0	♣
127-18-4	tetrachloroethylene (PCE)	8010	Groundwater	GC-Hall	0.03	0.3		0.2 - 10	8.58E-1		4.15E+0	
127-18-4	tetrachloroethylene (PCE)	8240	Groundwater	GC/MS		5		0.2 - 10	8.58E-1	♣	4.15E+0	♣
5216-25-1	tetrachlorotoluene;P,a,a,a-								4.38E-3			
961-11-5	tetrachlorvinphos	8140	Groundwater	GC-FPD		2		0.25 - 2	3.65E+0			
108-88-3	toluene	502.2	Drinking Water	GC-PID	0.01	0.1						
108-88-3	toluene	503.1	Drinking Water	GC-PID	0.02	0.2						
108-88-3	toluene	524.1	Drinking Water	GC/MS	0.1	1						
108-88-3	toluene	524.2	Drinking Water	GC/MS	0.11	1						
108-88-3	toluene	602	Wastewater	GC-PID	0.2	2						
108-88-3	toluene	624	Wastewater	GC/MS	6	60						
108-88-3	toluene	8020	Groundwater	GC-PID	0.2	2						
108-88-3	toluene	8240	Groundwater	GC/MS		5		0.5 - 10				
95-80-7	toluene-2,4-diamine								2.73E-2			
95-53-4	toluidine;o-	8270	Groundwater	GC/MS		10		1 - 10	3.65E-1	♣		
8001-35-2	toxaphene	505	Drinking Water	GC	1	10			7.95E-2	♣	4.50E-4	♣
8001-35-2	toxaphene	608/8080	Waste/Groundwater	GC-ECD	0.24	2			7.95E-2	♣	4.50E-4	♣
93-72-1	TP;2,4,5- (Silvex)	615/8150	Waste/Groundwater	GC-ECD	0.17	2		0.5 - 2				
93-72-1	TP;2,4,5- (Silvex)	515.1	Water	GC-ECD	0.075	0.8						
120-82-1	trichlorobenzene;1,2,4-	502.2	Drinking Water	GC-PID	0.02	0.2						
120-82-1	trichlorobenzene;1,2,4-	503.1	Drinking Water	GC-PID	0.03	0.3						
120-82-1	trichlorobenzene;1,2,4-	524.2	Drinking Water	GC/MS	0.04	0.4						
120-82-1	trichlorobenzene;1,2,4-	625	Wastewater	GC/MS	1.9	19						
120-82-1	trichlorobenzene;1,2,4-	8270	Groundwater	GC/MS		10		1 - 10				
120-82-1	trichlorobenzene;1,2,4-	612/8120	Waste/Groundwater	GC-ECD	0.05	0.5		0.5 - 1				
71-55-6	trichloroethane;1,1,1-	502.1	Drinking Water	GC	0.003	0.03						
71-55-6	trichloroethane;1,1,1-	502.2	Drinking Water	GC-PID	0.03	0.3						
71-55-6	trichloroethane;1,1,1-	524.1	Drinking Water	GC/MS	0.3	3						
71-55-6	trichloroethane;1,1,1-	524.2	Drinking Water	GC/MS	0.08	0.8						
71-55-6	trichloroethane;1,1,1-	601	Wastewater	GC	0.03	0.3						
71-55-6	trichloroethane;1,1,1-	624	Wastewater	GC/MS	3.8	38						
71-55-6	trichloroethane;1,1,1-	8010	Groundwater	GC	0.03	0.3		0.2 - 2				
71-55-6	trichloroethane;1,1,1-	8240	Groundwater	GC/MS		5		0.2 - 10				
79-00-5	trichloroethane;1,1,2-	502.1	Drinking Water	GC	0.007	0.07			7.68E-1		2.53E+1	
79-00-5	trichloroethane;1,1,2-	502.2	Drinking Water	GC-PID	0.04	0.4			7.68E-1		2.53E+1	
79-00-5	trichloroethane;1,1,2-	524.1	Drinking Water	GC/MS					7.68E-1		2.53E+1	

n/c = not calculated

pqlh2o.xls

TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag=na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag=na)
79-00-5	trichloroethane;1,1,2-	524.2	Drinking Water	GC/MS	0.1	1			7.68E-1		2.53E+1	
79-00-5	trichloroethane;1,1,2-	601	Wastewater	GC	0.02	0.2			7.68E-1		2.53E+1	
79-00-5	trichloroethane;1,1,2-	624	Wastewater	GC/MS	5	50			7.68E-1		2.53E+1	
79-00-5	trichloroethane;1,1,2-	8010	Groundwater	GC	0.02	0.2		0.2 - 10	7.68E-1		2.53E+1	
79-00-5	trichloroethane;1,1,2-	8240	Groundwater	GC/MS		5		0.5 - 10	7.68E-1		2.53E+1	
79-01-6	trichloroethylene (TCE)	502.1	Drinking Water	GC	0.001	0.01			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	502.2	Drinking Water	GC-ECD	0.01	0.1			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	503.1	Drinking Water	GC-PID	0.01	0.1			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	524.1	Drinking Water	GC/MS	0.4	4			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	524.2	Drinking Water	GC/MS	0.19	2			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	601	Wastewater	GC	0.12	1			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	624	Wastewater	GC/MS	1.9	19			3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	8010	Groundwater	GC-Hall	0.12	1		1 - 5	3.98E+0		5.56E+1	
79-01-6	trichloroethylene (TCE)	8240	Groundwater	GC/MS		5		2 - 5	3.98E+0		5.56E+1	
75-69-4	trichlorofluoromethane	502.1	Drinking Water	GC-Hall								
75-69-4	trichlorofluoromethane	502.2	Drinking Water	GC-ECD	0.03	0.3						
75-69-4	trichlorofluoromethane	524.1	Drinking Water	GC/MS	0.2	2						
75-69-4	trichlorofluoromethane	524.2	Drinking Water	GC/MS	0.08	0.8						
75-69-4	trichlorofluoromethane	601	Wastewater	GC-Hall								
75-69-4	trichlorofluoromethane	624	Wastewater	GC/MS								
75-69-4	trichlorofluoromethane	8010	Groundwater	GC-Hall								
95-95-4	trichlorophenol;2,4,5-	8270	Groundwater	GC/MS		10		0.1 - 10				
88-06-2	trichlorophenol;2,4,6-	625	Wastewater	GC/MS	2.7	27		8 - 27	7.95E+0		3.93E+0	
88-06-2	trichlorophenol;2,4,6-	8270	Groundwater	GC/MS		10		8 - 10	7.95E+0		3.93E+0	
88-06-2	trichlorophenol;2,4,6-	604/8040	Waste/Groundwater	GC-FID	0.64	6		0.1 - 10	7.95E+0		3.93E+0	
88-06-2	trichlorophenol;2,4,6-			GC-ECD	0.58	6		2 - 8	7.95E+0		3.93E+0	
93-76-5	trichlorophenoxyacetic acid;2,4,5-	515.1	Water	GC-ECD	0.08	0.8						
93-76-5	trichlorophenoxyacetic acid;2,4,5-	615/8150	Waste/Groundwater	GC-ECD	0.2	2		0.5 - 2				
512-56-1	trimethyl phosphate	8270	Groundwater	GC/MS		10		1 - 10	2.36E+0			
108-05-4	vinyl acetate	8240	Groundwater	GC/MS		50		1 - 50				
75-01-4	vinyl chloride	502.1	Drinking Water	GC	0.01	0.1			2.30E-2		2.92E+0	
75-01-4	vinyl chloride	502.2	Drinking Water	GC-PID	0.02	0.2			2.30E-2		2.92E+0	
75-01-4	vinyl chloride	524.1	Drinking Water	GC/MS	0.3	3			2.30E-2		2.92E+0	
75-01-4	vinyl chloride	524.2	Drinking Water	GC/MS	0.17	2			2.30E-2		2.92E+0	
75-01-4	vinyl chloride	624	Wastewater	GC/MS		10		1 - 10	2.30E-2		2.92E+0	
75-01-4	vinyl chloride	8240	Groundwater	GC/MS		10		1 - 10	2.30E-2		2.92E+0	

n/c = not calculated

pqlh2o.xls

TABLE I: WATER

MDLs, PQLs, and Comparison of Method B Values (µg/L)

Lab PQL Range < Published PQL

CAS	Chemical	Method	Matrix	Detector	MDL (µg/L)	PQL (µg/L)		LABORATORY PQL RANGE ug/L	Method B GW Value (µg/L) - C	PQL > GW Method B (flag = na)	Method B SW Value (µg/L) - C	PQL > SW Method B (flag = na)
75-01-4	vinyl chloride	601/8010	Waste/Groundwater	GC	0.18	2		2 - 10	2.30E-2		2.92E+0	
1330-20-7	xylene (total)	8020	Groundwater	GC-PID		5		0.5 - 10				
1330-20-7	xylene (total)	8240	Groundwater	GC/MS		5		0.5 - 10				
108-38-3	xylene;m-	502.2	Drinking Water	GC-PID	0.01	0.1						
108-38-3	xylene;m-	503.1	Drinking Water	GC-PID	0.004	0.04						
108-38-3	xylene;m-	524.1	Drinking Water	GC/MS								
108-38-3	xylene;m-	524.2	Drinking Water	GC/MS	0.05	0.5						
95-47-6	xylene;o-	502.2	Drinking Water	GC-PID	0.02	0.2						
95-47-6	xylene;o-	503.1	Drinking Water	GC-PID	0.004	0.04						
95-47-6	xylene;o-	524.1	Drinking Water	GC/MS	0.2	2						
95-47-6	xylene;o-	524.2	Drinking Water	GC/MS	0.11	1						
106-42-3	xylene;p-	502.2	Drinking Water	GC-PID	0.01	0.1			n/c		n/c	
106-42-3	xylene;p-	503.1	Drinking Water	GC-PID	0.002	0.02			n/c		n/c	
106-42-3	xylene;p-	524.1	Drinking Water	GC/MS	0.3	3			n/c		n/c	
106-42-3	xylene;p-	524.2	Drinking Water	GC/MS	0.13	1			n/c		n/c	
7440-66-6	zinc	200.7/6010	Water/Groundwater	ICP	2	20		0.5 - 50				
7440-66-6	zinc	289.1/7950	Water/Groundwater	FAA	5	50						
7440-66-6	zinc	289.2/7951	Water/Groundwater	GFAA	0.05	0.5						

n/c = not calculated

pqlh2o.xls

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
83-32-9	acenaphthene	8270	GC/MS		0.66		0.013 - 0.66		
83-32-9	acenaphthene	8310	HPLC	0.0018	1.2		0.017 - 1.2		
208-96-8	acenaphthylene	8270	GC/MS		0.66		0.017 - 0.66	n/c	
208-96-8	acenaphthylene	8310	HPLC	0.0023	1.5		0.017 - 1.5	n/c	
67-64-1	acetone	8240	GC/MS		0.01		0.001 - 0.05		
107-02-8	acrolein	8030	GC-FID	0.0007	0.007		0.001 - 0.01		
79-06-1	acrylamide	8015	GC-FID					2.22E-1	
107-13-1	acrylonitrile	8030	GC-FID	0.0005	0.005		0.001 - 0.05	1.85E+0	
15972-60-8	alachlor	505.2	GC-ECD		0.01			1.23E+1	
116-06-3	aldicarb	531.1	HPLC		0.5				
309-00-2	aldrin	8080	GC-ECD	4E-06	0.003		0.0017 - 0.003	5.88E-2	
62-53-3	aniline	8270	GC/MS		0.66		0.067 - 0.66	1.75E+2	
120-12-7	anthracene	8270	GC/MS		0.66		0.017 - 0.66		
120-12-7	anthracene	8310	HPLC	1.3E-05	0.009		0.005 - 0.009		
7440-36-0	antimony	6010	ICP	1.6	16		1.5 - 10		
7440-36-0	antimony	7041	AA	0.15	1.5		0.00025 - 1		
140-57-8	aramite	8270	GC/MS					4.00E+1	
12674-11-2	Aroclor 1016 (PCB)	8080	GC-ECD		0.044		0.017 - 0.1		
11104-28-2	Aroclor 1221 (PCB)	8080	GC-ECD		0.044		0.017 - 0.1	n/c	
11141-16-5	Aroclor 1232 (PCB)	8080	GC-ECD		0.044		0.017 - 0.1	n/c	
53469-21-9	Aroclor 1242 (PCB)	8080	GC-ECD		0.044		0.017 - 0.1	n/c	
12672-29-6	Aroclor 1248 (PCB)	8080	GC-ECD		0.044		0.017 - 0.1	n/c	
11097-69-1	Aroclor 1254 (PCB)	8080	GC-ECD		0.088		0.017 - 0.1	n/c	
11096-82-5	Aroclor 1260 (PCB)	8080	GC-ECD		0.088		0.017 - 0.1	n/c	
7440-38-2	arsenic	6010	ICP	2.5	25		2.5 - 10	1.43E+0	
7440-38-2	arsenic	7060	GFAA	0.05	0.5		0.00025 - 0.5	1.43E+0	
7440-38-2	arsenic	7061	GHAA	0.1	1			1.43E+0	
1332-21-4	asbestos								
1912-24-9	atrazine	619	GC/NP		0.05			4.55E+0	
103-33-3	azobenzene	8270	GC/MS		0.33		0.033 - 0.33	9.09E+0	
56-55-3	benz[a]anthracene	8270	GC/MS		0.66		0.0055 - 0.66	1.37E-1	
56-55-3	benz[a]anthracene	8310	HPLC	1.3E-05	0.009		0.005 - 0.009	1.37E-1	
71-43-2	benzene	8020	GC-PID	0.0002	0.002		0.001 - 0.04	3.45E+1	

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
71-43-2	benzene	8240	GC/MS		0.005		0.001 - 0.01	3.45E+1	
92-87-5	benzidine	8250	GC/MS	0.044	29		0.8 - 29	4.35E-3	
50-32-8	benzo[a]pyrene	8270	GC/MS		0.66		0.005 - 0.66	1.37E-1	
50-32-8	benzo[a]pyrene	8310	HPLC	2.3E-05	0.015		0.005 - 0.015	1.37E-1	
205-99-2	benzo[b]fluoranthene	8270	GC/MS		0.66		0.005 - 0.66	1.37E-1	
205-99-2	benzo[b]fluoranthene	8310	HPLC	1.8E-05	0.012		0.005 - 0.012	1.37E-1	
191-24-2	benzo[g,h,i]perylene	8270	GC/MS		0.66		0.01 - 0.66	n/c	
191-24-2	benzo[g,h,i]perylene	8310	HPLC	7.6E-05	0.051		0.01 - 0.051	n/c	
207-08-9	benzo[k]fluoranthene	8270	GC/MS		0.66		0.005 - 0.66	1.37E-1	
207-08-9	benzo[k]fluoranthene	8310	HPLC	1.7E-05	0.011		0.005 - 0.011	1.37E-1	
65-85-0	benzoic acid	8270	GC/MS		3.3		0.1 - 3.3		
98-07-7	benzotrichloride	8270/8010	GC-MS/GC-Hall		0.05		0.05 - 0.33	7.69E-2	
100-51-6	benzyl alcohol	8270	GC/MS		1.3		0.033 - 1.7		
100-44-7	benzyl chloride	8240	GC/MS		0.1		0.1 - 0.33	5.88E+0	
7440-41-7	beryllium	6010	ICP	0.015	0.15		0.125 - 0.25	2.33E-1	
7440-41-7	beryllium	7091	GFAA	0.01	0.1		0.125 - 0.25	2.33E-1	
111-91-1	bis(2-chloroethoxy)methane	8270	GC/MS		0.66		0.033 - 0.66	n/c	
111-44-4	bis(2-chloroethyl)ether (BCEE	8270	GC/MS		0.66		0.017 - 0.66	9.09E-1	
39638-32-9	bis(2-chloroisopropyl)ether	8270	GC/MS		0.66		0.067 - 0.66		
117-81-7	bis(2-ethylhexyl) phthalate (B	8270	GC/MS		0.66		0.017 - 0.66	7.14E+1	
542-88-1	bis(chloromethyl)ether (BCME	8270	GC/MS		0.66		0.01 - 0.66	4.55E-3	
75-27-4	bromodichloromethane (THM	8010	GC-Hall	0.0001	0.001		0.001 - 0.1	1.61E+1	
75-27-4	bromodichloromethane (THM	8240	GC/MS		0.005		0.001 - 0.01	1.61E+1	
75-25-2	bromoform (THM)	8010	GC-Hall	0.0002	0.002		0.001 - 0.5	1.27E+2	
75-25-2	bromoform (THM)	8240	GC/MS		0.005		0.001 - 0.01	1.27E+2	
101-55-3	bromophenyl phenyl ether;4-	8270	GC/MS		0.66		0.017 - 0.66	n/c	
85-68-7	butyl benzyl phthalate	8060	GC-FID	0.015	10				
85-68-7	butyl benzyl phthalate	8270	GC/MS		0.66		0.033 - 0.66		
85-68-7	butyl benzyl phthalate		GC-ECD	0.00034	0.23				
7440-43-9	cadmium	6010	ICP	0.2	2		0.01 - 1		
7440-43-9	cadmium	7130	GFAA	0.005	0.05		0.05 - 0.25		
86-74-8	carbazole	8270	GC/MS		0.33			5.00E+1	
1563-66-2	carbofuran	632	HPLC		0.83				

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
75-15-0	carbon disulfide	8240	GC/MS		0.1		0.001 - 0.05		
56-23-5	carbon tetrachloride	8010	GC-Hall	0.00012	0.001		0.001 - 0.01	7.69E+0	
56-23-5	carbon tetrachloride	8240	GC/MS		0.005		0.001 - 0.01	7.69E+0	
57-74-9	chlordane	8080	GC-ECD	1.4E-05	0.009		0.009 - 0.05	7.69E-1	
	chlordane; alpha	8080	GC-ECD		0.01		0.0017 - 0.01	n/c	
	chlordane; gamma	8080	GC-ECD		0.01		0.0017 - 0.01	n/c	
3165-93-3	chloro-2-methylaniline hydroch	8270	GC/MS		0.66		0.33 - 0.66	2.17E+0	
95-69-2	chloro-2-methylaniline;4-	8270	GC/MS		0.66		0.66 - 1.7	1.72E+0	
59-50-7	chloro-3-methylphenol;4-	8040	GC-ECD	0.0018	1.2			n/c	
59-50-7	chloro-3-methylphenol;4-	8040	GC-FID	0.00036	0.24			n/c	
106-47-8	chloroaniline;4-	8270	GC/MS		0.33		0.067 - 0.33		
108-90-7	chlorobenzene	8010	GC-Hall	0.00025	0.003		0.001 - 0.025		
108-90-7	chlorobenzene	8020	GC-PID	0.0002	0.002		0.001 - 0.01		
108-90-7	chlorobenzene	8240	GC/MS		0.005		0.001 - 0.01		
124-48-1	chlorodibromomethane	8010	GC-Hall		0.002		0.001 - 0.1	1.19E+1	
75-00-3	chloroethane	8010	GC-Hall	0.00052	0.005		0.001 - 0.5		
75-00-3	chloroethane	8240	GC/MS		0.01		0.001 - 0.01		
110-75-8	chloroethyl vinyl ether;2-	8010	GC-Hall	0.00013	0.001		0.001 - 0.5	n/c	
110-75-8	chloroethyl vinyl ether;2-	8240	GC/MS		0.01		0.001 - 0.01	n/c	
67-66-3	chloroform	8010	GC-Hall	0.00005	0.0005		0.0005 - 0.05	1.64E+2	
67-66-3	chloroform	8240	GC/MS		0.005		0.001 - 0.01	1.64E+2	
74-87-3	chloromethane	8010	GC-Hall	0.00008	0.0008		0.0008 - 0.5	7.69E+1	
74-87-3	chloromethane	8240	GC/MS		0.01		0.001 - 0.01	7.69E+1	
91-58-7	chloronaphthalene;2-	8120	GC-Hall	0.00094	0.63		0.33 - 0.63	n/c	
91-58-7	chloronaphthalene;2-	8270	GC/MS		0.66		0.017 - 0.66	n/c	
88-73-3	chloronitrobenzene;o-	8270	GC/MS		0.66		0.33 - 0.66	4.00E+1	
100-00-5	chloronitrobenzene;p-	8270	GC/MS		0.66		0.33 - 0.66	5.56E+1	
95-57-8	chlorophenol;2-	8040	GC-FID	0.00031	0.21		0.33 - 1.5		
95-57-8	chlorophenol;2-	8270	GC/MS		0.66		0.17 - 0.66		
95-57-8	chlorophenol;2-		GC-ECD	0.00058	0.39		0.067 - 0.39		
7005-72-3	chlorophenyl phenyl ether;4-	8270	GC/MS		0.66		0.017 - 0.66	n/c	
1897-45-6	chlorthalonil	8080	GC-ECD		0.01		0.0083 - 0.01	9.09E+1	
16065-83-1	chromium(III) (**)	3050/7190	FAA	2.5	25		0.25 - 1		

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
16065-83-1	chromium(III) (**)	3050/7191	GFAA	0.05	0.5		0.25 - 0.5		
7440-47-3	chromium(VI) (**)							n/c	
218-01-9	chrysene	8270	GC/MS		0.66		0.01 - 0.66	1.37E-1	
218-01-9	chrysene	8310	HPLC	0.00015	0.1		0.01 - 0.1	1.37E-1	
7440-50-8	copper	6010	ICP	0.3	3		0.5 - 1		
7440-50-8	copper	7211	GFAA	0.05	0.5				
108-39-4	cresol;m-	8270	GC/MS		0.66		0.033 - 0.66		
95-48-7	cresol;o-	8270	GC/MS		0.66		0.033 - 0.66		
106-44-5	cresol;p-	8270	GC/MS		0.66		0.033 - 0.66		
57-12-5	cyanide	SM4500-CN	color		5		0.5 - 5		
75-99-0	dalapon, sodium salt	8150	GC-ECD	0.0058	1.2		0.1 - 1.2		
94-82-6	DB;2,4-	8150	GC-ECD	0.00091	0.18				
72-54-8	DDD;p,p'-	8080	GC-ECD	1.1E-05	0.007		0.0017 - 0.007	4.17E+0	
72-55-9	DDE;p,p'-	8080	GC-ECD	4E-06	0.003		0.0017 - 0.1	2.94E+0	
50-29-3	DDT;p,p'-	8080	GC-ECD	1.2E-05	0.008		0.0017 - 0.1	2.94E+0	
84-74-2	di-n-butyl phthalate	8060	GC-ECD	0.00036	0.004				
84-74-2	di-n-butyl phthalate	8270	GC/MS	0.0025	1.7		0.033 - 1.7		
117-84-0	di-n-octyl phthalate	8060	GC-ECD	0.003	0.03				
117-84-0	di-n-octyl phthalate	8270	GC/MS		0.66		0.017 - 0.66		
2303-16-4	diallate	8150	GC-ECD		0.15			1.64E+1	
333-41-5	diazinon	8140	GC-FPD	0.0006	0.12		0.0017 - 0.033		
53-70-3	dibenz[a,h]anthracene	8270	GC/MS		0.66		0.01 - 0.66	1.37E-1	
53-70-3	dibenz[a,h]anthracene	8310	HPLC	0.00003	0.02		0.01 - 0.66	1.37E-1	
132-64-9	dibenzofuran	8270	GC/MS		0.33		0.033 - 0.33		
124-48-1	dibromochloromethane (THM	8010	GC-Hall	0.00009	0.0009		0.0009 - 0.1	1.19E+1	
124-48-1	dibromochloromethane (THM	8240	GC/MS		0.005		0.001 - 0.01	1.19E+1	
124-48-1	dibromochloromethane (THM	8240	GC/MS		0.005		0.001 - 0.01	1.19E+1	
1918-00-9	dicamba	8150	GC-ECD	0.00027	0.054		0.01 - 0.3		
95-50-1	dichlorobenzene;1,2-	8010	GC-Hall	0.00015	0.0015		0.0015 - 0.1		
95-50-1	dichlorobenzene;1,2-	8020	GC-PID	0.0004	0.004		0.004 - 0.01		
95-50-1	dichlorobenzene;1,2-	8120	GC-ECD	0.00114	0.76		0.01 - 0.76		
95-50-1	dichlorobenzene;1,2-	8270	GC/MS		0.66		0.017 - 0.66		
541-73-1	dichlorobenzene;1,3-	8010	GC-Hall	0.00032	0.0032		0.0032 - 0.33	n/c	

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
541-73-1	dichlorobenzene;1,3-	8020	GC-PID	0.0004	0.004		0.004 - 0.33	n/c	
541-73-1	dichlorobenzene;1,3-	8120	GC-ECD	0.00119	0.8		0.01 - 0.8	n/c	
541-73-1	dichlorobenzene;1,3-	8270	GC/MS		0.66		0.017 - 0.66	n/c	
106-46-7	dichlorobenzene;1,4-	8010	GC-Hall	0.00024	0.0024		0.0024 - 0.33	4.17E+1	
106-46-7	dichlorobenzene;1,4-	8020	GC-PID	0.0003	0.003		0.003 - 0.33	4.17E+1	
106-46-7	dichlorobenzene;1,4-	8120	GC-ECD	0.00134	0.9		0.33 - 0.9	4.17E+1	
106-46-7	dichlorobenzene;1,4-	8270	GC/MS		0.66		0.01 - 0.66	4.17E+1	
91-94-1	dichlorobenzidine;3,3-	8270	GC/MS		1.3		0.033 - 1.3	2.22E+0	
75-71-8	dichlorodifluoromethane	8010	GC-Hall		0.002		0.001 - 0.02		
75-71-8	dichlorodifluoromethane	8240	GC/MS		0.005		0.001 - 0.05		
75-34-3	dichloroethane;1,1-	8010	GC-Hall	0.00007	0.0007		0.0007 - 0.01		
75-34-3	dichloroethane;1,1-	8240	GC/MS		0.005		0.001 - 0.1		
107-06-2	dichloroethane;1,2-	8010	GC-Hall	0.00003	0.0003		0.0003 - 0.01	1.10E+1	
107-06-2	dichloroethane;1,2-	8240	GC/MS		0.005		0.001 - 0.1	1.10E+1	
156-60-5	dichloroethene;1,2-trans-	8010	GC-Hall	0.0001	0.001		0.001 - 0.05		
156-60-5	dichloroethene;1,2-trans-	8240	GC/MS		0.005		0.001 - 0.01		
75-35-4	dichloroethylene;1,1-	8010	GC-Hall	0.00013	0.001		0.001 - 0.05	1.67E+0	
75-35-4	dichloroethylene;1,1-	8240	GC/MS		0.005		0.001 - 0.01	1.67E+0	
540-59-0	dichloroethylene;1,2-	8010	GC-Hall	0.00013	0.001		0.001 - 0.01	n/c	
540-59-0	dichloroethylene;1,2-	8240	GC/MS		0.005		0.001 - 0.01	n/c	
156-59-2	dichloroethylene;1,2-cis-	8010	GC-Hall	0.00013	0.001		0.001 - 0.01		
156-59-2	dichloroethylene;1,2-cis-	8240	GC/MS		0.005		0.001 - 0.01		
120-83-2	dichlorophenol;2,4-	8040	GC-FID	0.00039	0.26		0.033 - 0.33		
120-83-2	dichlorophenol;2,4-	8270	GC/MS		0.66		0.033 - 1.7		
120-83-2	dichlorophenol;2,4-		GC-ECD	0.00068	0.46				
94-75-7	dichlorophenoxyacetic acid;2,4	8150	GC-ECD	0.0012	0.24		0.04 - 1		
78-87-5	dichloropropane;1,2-	8010	GC-Hall	0.00004	0.0004		0.0004 - 0.1	1.47E+1	
78-87-5	dichloropropane;1,2-	8240	GC/MS		0.005		0.001 - 0.01	1.47E+1	
542-75-6	dichloropropene;1,3- (total)	8010	GC-Hall	0.00034	0.003		0.001 - 0.01	5.56E+0	
542-75-6	dichloropropene;1,3- (total)	8240	GC/MS		0.005		0.001 - 0.01	5.56E+0	
	dichloropropene;1,3-cis-	8010	GC-Hall	0.00034	0.003		0.001 - 0.2	n/c	
	dichloropropene;1,3-cis-	8240	GC/MS		0.005		0.001 - 0.01	n/c	
	dichloropropene;1,3-trans	8240	GC/MS		0.005		0.001 - 0.1	n/c	

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
	dichloropropene;1,3-trans-	8010	GC-Hall	0.00034	0.003		0.001 - 0.01	n/c	
60-57-1	dieldrin	8080	GC-ECD	2E-06	0.001		0.001 - 0.01	6.25E-2	
84-66-2	diethyl phthalate	8060	GC-FID	0.031	21				
84-66-2	diethyl phthalate	8270	GC/MS		0.66		0.033 - 0.66		
84-66-2	diethyl phthalate		GC-ECD	0.00049	0.33				
119-90-4	dimethoxybenzidine;3,3'-	8270	GC/MS		1		0.33 - 1	7.14E+1	
131-11-3	dimethyl phthalate	8060	GC-FID	0.019	13				
131-11-3	dimethyl phthalate	8270	GC/MS		0.66		0.01 - 0.66		
131-11-3	dimethyl phthalate		GC-ECD	0.00029	0.19		0.19 - 0.33		
119-93-7	dimethylbenzidine;3,3'-	8270	GC/MS		1		0.33 - 1	1.09E-1	
540-73-8	dimethylhydrazine;1,2-	8270	GC/MS		1		1 - 1.7	7.14E-4	
105-67-9	dimethylphenol;2,4-	8040	GC-FID	0.00032	0.21				
105-67-9	dimethylphenol;2,4-	8270	GC/MS		0.66		0.033 - 0.66		
105-67-9	dimethylphenol;2,4-		GC-ECD	0.00063	0.42				
534-52-1	dinitro-o-cresol;4,6-	8270	GC/MS		3.3		0.033 - 3.3	n/c	
51-28-5	dinitrophenol;2,4-	8040	GC-FID	0.013	8.7		0.067 - 8.7		
51-28-5	dinitrophenol;2,4-	8270	GC/MS		3.3		0.067 - 3.3		
121-14-2	dinitrotoluene;2,4-	8090	GC-ECD	0.00002	0.013		0.013 - 0.33		
121-14-2	dinitrotoluene;2,4-	8270	GC/MS		0.66		0.013 - 0.66		
606-20-2	dinitrotoluene;2,6-	8090	GC-ECD	0.00001	0.007		0.007 - 0.66		
606-20-2	dinitrotoluene;2,6-	8270	GC/MS		0.66		0.013 - 0.66		
88-85-1	dinoseb	8150	GC-ECD	0.00007	0.014		0.0017 - 0.05		
88-85-1	dinoseb	8270	GC/MS						
123-91-1	dioxane;1,4-	8240	GC/MS		0.01		0.01 - 0.5	9.09E+1	
122-66-7	diphenylhydrazine;1,2-	8270	GC/MS		0.66		0.067 - 0.66	1.25E+0	
298-04-4	disulfoton	8140	GC-FPD	0.0002	0.13		0.0017 - 0.13		
298-04-4	disulfoton	8270	GC/MS						
	endosulfan (alpha, beta)	8080	GC-ECD					n/c	
	endosulfan I	8080	GC-ECD	1.4E-05	0.009		0.0017 - 0.1	n/c	
	endosulfan II	8080	GC-ECD	4E-06	0.003		0.0017 - 0.1	n/c	
1031-07-8	endosulfan sulfate	8080	GC-ECD	6.6E-05	0.044		0.0017 - 0.1	n/c	
145-73-3	endothall								
72-20-8	endrin	8080	GC-ECD	6E-06	0.004		0.0017 - 0.1		

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
53494-70-5	endrin ketone	8250	GC/MS					n/c	
106-89-8	epichlorohydrin							1.01E+2	
140-88-5	ethyl acrylate	8020	GC-PID		0.1		0.1 - 0.33	2.08E+1	
100-41-4	ethylbenzene	8020	GC-PID	0.0002	0.002		0.001 - 0.04		
100-41-4	ethylbenzene	8240	GC/MS		0.005		0.001 - 0.01		
106-93-4	ethylene dibromide (EDB)	8011	GC/ECD		0.002		0.002 - 0.005	1.18E-2	
107-21-1	ethylene glycol	8240	GC-FID		10		0.33 - 10		
96-45-7	ethylene thiourea	*632	HPLC					2.78E+1	
206-44-0	fluoranthene	8270	GC/MS		0.66		0.005 - 0.66		
206-44-0	fluoranthene	8310	HPLC	0.00021	0.14		0.01 - 0.14		
86-73-7	fluorene	8270	GC/MS		0.66		0.005 - 0.66		
86-73-7	fluorene	8300	HPLC	0.00021	0.14		0.005 - 0.14		
133-07-3	folpet							2.86E+2	
67-45-8	furazolidone							2.63E-1	
531-82-8	furium							2.00E-2	
76-44-8	heptachlor	8080	GC-ECD	3E-06	0.002		0.0017 - 0.1	2.22E-1	
1024-57-3	heptachlor epoxide	8080	GC-ECD	8.3E-05	0.056		0.0017 - 0.1	1.10E-1	
118-74-1	hexachlorobenzene	8120	GC-ECD	0.00005	0.034		0.034 - 0.33	6.25E-1	
118-74-1	hexachlorobenzene	8270	GC/MS		0.66		0.017 - 0.66	6.25E-1	
87-68-3	hexachlorobutadiene	8120	GC-ECD	0.00034	0.23		0.23 - 0.33	1.28E+1	
87-68-3	hexachlorobutadiene	8270	GC/MS		0.66		0.033 - 0.66	1.28E+1	
319-84-6	hexachlorocyclohexane;alpha	8080	GC-ECD	3E-06	0.002		0.0017 - 0.002	1.59E-1	
319-85-7	hexachlorocyclohexane;beta	8080	GC-ECD	6E-06	0.004		0.0017 - 0.004	5.56E-1	
319-86-8	hexachlorocyclohexane;delta	8080	GC-ECD	9E-06	0.006		0.0017 - 0.006		
58-89-9	hexachlorocyclohexane;gamm	8080	GC-ECD	4E-06	0.003		0.0017 - 0.008	7.69E-1	
58-89-9	hexachlorocyclohexane;gamm	8270	GC/MS					7.69E-1	
77-47-4	hexachlorocyclopentadiene	8120	GC-ECD	0.0004	0.27		0.27 - 0.33		
77-47-4	hexachlorocyclopentadiene	8270	GC/MS		0.66		0.033 - 0.66		
67-72-1	hexachloroethane	8120	GC-ECD	0.00003	0.02		0.02 - 0.33	7.14E+1	
67-72-1	hexachloroethane	8270	GC/MS		0.66		0.033 - 0.66	7.14E+1	
591-78-6	hexanone;2-	8240	GC/MS		0.05		0.001 - 0.05	n/c	
302-01-2	hydrazine sulfate	8270	GC/MS		1.3			3.33E-1	
193-39-5	Indeno[1,2,3-c,d]pyrene	8270	GC/MS		0.66		0.01 - 0.66		

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
193-39-5	Indeno[1,2,3-c,d]pyrene	8310	HPLC	4.3E-05	0.029		0.01 - 0.029		
78-59-1	Isophorone	8090	GC-FID	0.0057	3.8		0.33 - 3.8	1.05E+3	
78-59-1	Isophorone	8270	GC/MS		0.66		0.033 - 0.66	1.05E+3	
78-59-1	Isophorone		GC-ECD	0.0157	11			1.05E+3	
7439-92-1	lead	6010	ICP	2.1	21		1.25 - 8		
7439-92-1	lead	7420	FAA	5	50		0.125 - 0.5		
7439-92-1	lead	7421	GFAA	0.05	0.5		0.125 - 0.5		
121-75-5	malathion	8150	GC-FPD	0.0055	0				
7439-97-6	mercury (inorganic)	7470	AA	0.0002	0.002		0.125 - 0.5		
7439-97-6	mercury (inorganic)	7471	AA	0.0002	0.002		0.1 - 1		
72-43-5	methoxychlor	8080	GC-ECD	0.00018	0.12		0.0017 - 0.12		
72-43-5	methoxychlor	8270	GC/MS						
74-83-9	methyl bromide	9011	GC-ECD		0.01		0.001 - 0.01		
78-93-3	methyl ethyl ketone (MEK)	8015	GC-FID		0.1		0.001 - 0.05		
78-93-3	methyl ethyl ketone (MEK)	8240	GC/MS		0.01		0.001 - 0.05		
108-10-1	methyl isobutyl ketone (MIBK	8015	GC-FID		0.1		0.001 - 0.05		
108-10-1	methyl isobutyl ketone (MIBK	8240	GC/MS		0.01		0.001 - 0.05		
298-00-0	methyl parathion	8140	GC-FPD	0.00003	0.02		0.005 - 0.02		
94-74-6	methyl-4-chlorophenoxy-acetic	8150	GC-ECD	0.249	50		5 - 50		
636-21-5	methylanaline hydrochloride;2-	8270	GC/MS		0.66		0.33 - 0.66	5.56E+0	
	methylanaline;2-	8270	GC/MS		0.66		0.33 - 0.66	n/c	
75-09-2	methylene chloride	8010	GC-Hall				0.001 - 0.01	1.33E+2	
75-09-2	methylene chloride	8240	GC/MS		0.005		0.001 - 0.01	1.33E+2	
	methylnaphthalene;2-	8270	GC/MS		0.66		0.017 - 0.66	n/c	
2385-85-5	mirex	8270	GC/MS					5.56E-1	
91-20-3	naphthalene	8100	GC-FID		0.66		0.05 - 0.66		
91-20-3	naphthalene	8270	GC/MS		0.66		0.005 - 0.66		
91-20-3	naphthalene	8310	HPLC	0.0018	1.2		0.05 - 1.2		
unavailable03	nickel, refinery dust (*)	6010	ICP	0.75	7.5		1 - 4		
7440-02-0	nickel, sol. salts	7520	FAA	2	20				
88-74-4	nitroaniline;2-	8270	GC/MS		3.3		0.1 - 33	n/c	
99-09-2	nitroaniline;3-	8270	GC/MS		3.3		0.1 - 33	n/c	
100-01-6	nitroaniline;4-	8270	GC/MS		1.6		0.1 - 33	n/c	

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
98-95-3	nitrobenzene	8090	GC-FID	0.0036	2.4		1.7 - 2.4		
98-95-3	nitrobenzene	8270	GC/MS		0.66		0.033 - 0.66		
98-95-3	nitrobenzene		GC-ECD	0.0137	9.2		0.33 - 9.2		
59-87-0	nitrofurazone							6.67E-1	
	nitrophenol;2-	8040	GC-FID	0.00045	0.3			n/c	
	nitrophenol;2-	8270	GC/MS		0.66			n/c	
	nitrophenol;2-		GC-ECD	0.00077	0.52		0.033 - 0.52	n/c	
	nitrophenol;4-	8040	GC-FID	0.0028	1.9			n/c	
	nitrophenol;4-	8270	GC/MS		3.3			n/c	
	nitrophenol;4-		GC-ECD	0.0007	0.47			n/c	
924-16-3	nitroso-di-n-butylamine;N-	8070	GC-Hall/GC-NP					1.85E-1	
924-16-3	nitroso-di-n-butylamine;N-	8250	GC/MS		1.3		0.33 - 1.3	1.85E-1	
621-64-7	nitroso-di-n-propylamine;N-	8070	GC-Hall/GC-NP					1.43E-1	
621-64-7	nitroso-di-n-propylamine;N-	8250	GC/MS		1.3		0.033 - 1.3	1.43E-1	
1116-54-7	nitrosodiethanolamine;N-	8070	GC-Hall/GC-NP					3.57E-1	
1116-54-7	nitrosodiethanolamine;N-	8270	GC/MS		1.3		0.33 - 1.3	3.57E-1	
55-18-5	nitrosodiethylamine;N-	8070	GC-Hall/GC-NP					6.67E-3	
55-18-5	nitrosodiethylamine;N-	8270	GC/MS		1.3		0.33 - 1.3	6.67E-3	
62-75-9	nitrosodimethylamine;N- (DMN	8070	GC-Hall/GC-NP	0.00015	0.002			1.96E-2	
62-75-9	nitrosodimethylamine;N- (DMN	8270	GC/MS		1.3		0.33 - 1.3	1.96E-2	
86-30-6	nitrosodiphenylamine;N-	8070	GC-Hall/GC-NP	0.00081	0.008			2.04E+2	
86-30-6	nitrosodiphenylamine;N-	8270	GC/MS		0.66		0.033 - 0.66	2.04E+2	
10595-95-6	nitrosomethylethylamine;N-	8070	GC-Hall/GC-NP					4.55E-2	
10595-95-6	nitrosomethylethylamine;N-	8270	GC/MS		1.3		0.33 - 1.3	4.55E-2	
930-55-2	nitrosopyrrolidine;N-	8070	GC-Hall/GC-NP					4.76E-1	
930-55-2	nitrosopyrrolidine;N-	8270	GC/MS		1.3		0.33 - 1.3	4.76E-1	
56-38-2	parathion	8141	GC		0.06		0.0033 - 0.06		
608-93-5	pentachlorobenzene	8270	GC/MS						
87-86-5	pentachlorophenol (PCP)	8040	GC-FID	0.0074	5		0.067 - 5	8.33E+0	
87-86-5	pentachlorophenol (PCP)	8270	GC/MS		3.3			8.33E+0	
87-86-5	pentachlorophenol (PCP)		GC-ECD	0.00059	0.4			8.33E+0	
85-01-8	phenanthrene	8270	GC/MS		0.66		0.005 - 0.66	n/c	
85-01-8	phenanthrene	8310	HPLC	0.00064	0.43		0.0083 - 0.43	n/c	

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
108-95-2	phenol	8040	GC-FID	0.00014	0.094				
108-95-2	phenol	8270	GC/MS		0.66		0.1 - 1.5		
108-95-2	phenol		GC-ECD	0.0022	1.5				
93-65-2	propionic acid;2(2-methyl)-4-cl	8150	GC-ECD	0.192	38		5 - 38		
129-00-0	pyrene	8270	GC/MS		0.66		0.005 - 0.66		
129-00-0	pyrene	8310	HPLC	0.00027	0.18		0.01 - 0.18		
7782-49-2	selenium	6010	ICP	0.075	0.75		2.5 - 20		
7782-49-2	selenium	7740	GFAA	0.5	5		0.125 - 0.5		
7782-49-2	selenium	7741	GHAA	0.1	1				
7440-22-4	silver	6010		0.35	3.5				
7440-22-4	silver	7740		0.5	5		0.25 - 1		
7440-22-4	silver	7741		0.01	0.1		0.05 - 0.25		
122-34-9	simazine	619	GC/NP		0.33		0.033 - 0.33	8.33E+0	
100-42-5	styrene	8240	GC/MS		0.005		0.001 - 0.01	3.33E+1	
1746-01-6	TCDD;2,3,7,8- (dioxin)	8290	GC/MS	3E-07	0.000003			6.67E-6	
	TCDF;2,3,7,8-	8290	GC/MS	3E-07	0.000003			n/c	
95-94-3	tetrachlorobenzene;1,2,4,5-	8270	GC/MS		0.33				
79-34-5	tetrachloroethane;1,1,2,2-	8010	GC-Hall	0.00003	0.0003		0.0003 - 0.1	5.00E+0	
79-34-5	tetrachloroethane;1,1,2,2-	8240	GC/MS		0.005		0.001 - 0.01	5.00E+0	
127-18-4	tetrachloroethylene (PCE)	8010	GC-Hall	0.00003	0.0003		0.0003 - 0.05	1.96E+1	
5216-25-1	tetrachlorotoluene;P,a,a,a-							5.00E-2	
961-11-5	tetrachlorvinphos	8141	GC/FPD		0.4		0.005 - 0.4	4.17E+1	
108-88-3	toluene	8020	GC-PID	0.0002	0.002		0.001 - 0.025		
108-88-3	toluene	8240	GC/MS		0.005		0.001 - 0.01		
95-80-7	toluene-2,4-diamine							3.13E-1	
95-53-4	toluidine;o-	8270	GC/MS		0.33			4.17E+0	
8001-35-2	toxaphene	8080	GC-ECD	0.00024	0.16		0.017 - 1	9.09E-1	
93-72-1	TP;2,4,5- (Silvex)	8150	GC-ECD	0.00017	0.034		0.01 - 0.1		
120-82-1	trichlorobenzene;1,2,4-	8120	GC-ECD	0.00005	0.034		0.034 - 0.33		
120-82-1	trichlorobenzene;1,2,4-	8270	GC/MS		0.66		0.017 - 0.66		
71-55-6	trichloroethane;1,1,1-	8010	GC-Hall	0.00003	0.0003		0.0003 - 0.05		
71-55-6	trichloroethane;1,1,1-	8240	GC/MS		0.005		0.001 - 0.01		
79-00-5	trichloroethane;1,1,2-	8010	GC-Hall	0.00002	0.0002		0.0002 - 0.1	1.75E+1	

n/c = not calculated

TABLE II: SOIL

MDLs, PQLs, and Comparison of Method B Values

Lab PQL Range < Published PQL

CAS	Chemical	Method	Dectector	MDL (mg/kg)	PQL (mg/kg)		LABORATORY PQL RANGE (mg/kg)	10e-6 Method B Soil Value (mg/kg)	PQL > Soil Method B (flag=na)
79-00-5	trichloroethane;1,1,2-	8240	GC/MS		0.005		0.001 - 0.01	1.75E+1	
79-01-6	trichloroethene (TCE)	8010	GC-Hall	0.00012	0.001		0.001 - 0.01	9.09E+1	
75-69-4	trichlorofluoromethane	8010	GC-Hall		0.002		0.001 - 0.025		
75-69-4	trichlorofluoromethane	8240	GC/MS		0.005		0.001 - 0.01		
95-95-4	trichlorophenol;2,4,5-	8270	GC/MS		0.66		0.033 - 1.7		
88-06-2	trichlorophenol;2,4,6-	8040	GC-FID	0.00064	0.43		0.033 - 1.7	9.09E+1	
88-06-2	trichlorophenol;2,4,6-	8270	GC/MS		0.66			9.09E+1	
88-06-2	trichlorophenol;2,4,6-		GC-ECD	0.00058	0.39			9.09E+1	
93-76-5	trichlorophenoxyacetic acid;2,4	8150	GC-ECD	0.0002	0.04		0.01 - 0.2		
512-56-1	trimethyl phosphate	8270	GC/MS					2.70E+1	
108-05-4	vinyl acetate	8240	GC/MS		0.05		0.001 - 0.05		
75-01-4	vinyl chloride	8010	GC-Hall	0.00018	0.002		1	5.26E-1	
75-01-4	vinyl chloride	8240	GC/MS		0.02		0.001 - 0.01	5.26E-1	
1330-20-7	xylene (total)	8020	GC-PID		0.002		0.001 - 0.04		
1330-20-7	xylene (total)	8240	GC/MS		0.005		0.001 - 0.01		
108-38-3	xylene;m-	8020	GC-PID		0.002		0.001 - 0.01		
108-38-3	xylene;m-	8240	GC/MS	0.00013	0.005		0.001 - 0.01		
95-47-6	xylene;o-	8020	GC-PID		0.002		0.001 - 0.01		
95-47-6	xylene;o-	8240	GC/MS	0.00013	0.005		0.001 - 0.01		
106-42-3	xylene;p-	8020	GC-PID		0.002		0.001 - 0.01	n/c	
106-42-3	xylene;p-	8240	GC/MS	0.00013	0.005		0.001 - 0.01	n/c	
7440-66-6	zinc	6010	ICP	0.1	1		0.5 - 2		
7440-66-6	zinc	7951	AA	0.003	0.03				

n/c = not calculated

APPENDIX

MEANING OF QUANTITATION LIMITS

This guidance is Part IV of four parts. They are:

Part I:	*Implementation Memo No. 3--PQLs as Cleanup Standards*
Part II:	*Guidance For The Use of Tables*
Part III:	*MDL, PQL, and Comparisons Tables*
Part IV:	*Appendix--Meaning of Quantitation Limits (this document)*

In Part II, Guidance For The Use of Tables, an overview was given of the need for a site manager to have information on the lowest levels which can be routinely quantified and reported by a laboratory. These lowest levels are known as the "practical quantitation limits" (PQLs). The "method detection limit" (MDL) is used mostly by the laboratory analyst and not usually reported but can provide useful information to the site manager.

This document discusses the meaning of these two terms, PQL and MDL.

The MDL is defined by the EPA in Appendix B of 40 CFR 136 as "...the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero." Appendix B includes detailed procedures for determining the MDL either in lab reagent water or in the sample matrix.

Detection should be based on the variability of the response of the measurement system (such as a gas chromatograph) to a sample with zero concentration of the analyte (blank response). Detection limits should account for the probabilities of false positives and false negatives. The MDL is based on the variability of the response of the measurement system to a low level standard or spiked sample and accounts only for false positives.

Concentrations of chemicals that exceed the MDL but do not exceed the PQL are often reported as estimates.

There is no single accepted method for defining or determining the PQL. Some documents, including some by EPA, refer to "detection limits" without explanation of how they were derived. Many PQLs listed in federal regulations are based on consensus rather than rigorous technical assessments. The following is an excerpt from guidance for statistical regulations (U.S. EPA 1988):

> *"The PQLs listed were EPA's best estimate of the practical sensitivity of the applicable method for RCRA ground water monitoring purposes. However, some of the PQLs may be unattainable because they are based on general estimates for the specific substance. Furthermore, due to site-specific factors, these limits may not be reached. For these reasons, the agency feels that the PQLs listed in Appendix IX are not appropriate for establishing a national baseline value for each constituent for determining whether a release to ground water has occurred. Instead, the PQLs are viewed as target levels that chemical laboratories should try to achieve in their analysis of ground water."*

Soils usually present even more difficulty for analysis than groundwater because they have a more complex matrix to separate the contaminants from, often there are more contaminants present, and usually a smaller analytical sample is used. There is also often a wider range of contaminant concentrations to deal with. For these reasons, PQLs for soils are even more subject to variation than for groundwater.

The Model Toxics Control Act (MTCA) defines Practical Quantitation Limits:

> *"The lowest concentration that can be reliable measured within specified limits of precision, accuracy, representativeness, completeness, and comparability during routine laboratory operating condition, using department approved methods"* (WAC 173-340-200 Definitions).

Or more simply, the minimum level of a substance for which the question of how much of that substance is present, can be answered with a high degree of certainty. PQLs often are determined by evaluating performance results of inter-laboratories studies where artificial samples are analyzed to test each laboratory's ability to accurately measure a substance using a specific method.

Practical quantitation limits are expected to provide a lower bound on the technical feasibility of cleanup levels. Important factors that influence the quantitation limits include sample size, analytical method, instrument limits, and the analytical uncertainties in the sample matrix. Unfortunately, inter-laboratory studies cannot duplicate every matrix, especially those most difficult to analyze.

Ecology has put a threshold on the PQL in WAC 173-340-707 (2) Analytical considerations. The PQL must be the more stringent of the following conditions:

(a) The PQL may be no greater than ten times the method detection limit; or

(b) The PQL for a particular hazardous substance, medium, and analytical procedure may be no greater than the PQL established by the United States Environmental Protection Agency and used to establish requirements in 40 CFR 136, 40 CFR 141 through 143, or 40 CFR 260 through 270.

PQLs As Cleanup Levels

- Method A may use PQLs as the compliance levels. See WAC 173-340-704 (2)(c) Use of method A.

- Methods B or C may use PQLs as compliance levels for substances when the risk-based cleanup standard is below the PQL. See WAC 173-340-700 (6) Measuring compliance; WAC 173-340-707 (2) Analytical considerations; and Part I, Technical Information Memo No. 3--PQLs As Cleanup Standards for further discussion.

Survey Of Analytical Laboratories

A survey of analytical laboratories was conducted by the Department of Ecology in March of 1992. The purpose of the survey was to assess the performance capabilities of analytical laboratories in support of investigations under MTCA.

The survey data was used, in part, to develop the tables in Part III: MDL, PQL, and Comparisons Tables.

The purpose of the survey was to identify MDLs and PQLs that could be achieved by commercial laboratories on a regular basis. Laboratories have not been identified because the individual responses were considered confidential. Ecology does not recommend any specific laboratory. Someone requesting the services of a laboratory should ascertain the qualifications and ability of the laboratory to perform the desired work. These tables should help provide a comparison for MDLs or PQLs the laboratory may provide.

pqlappe$ sr

Selected Excerpts
from:

Methods for Evaluating the Attainment of Cleanup Standards.

Volume 1: Soils and Solid Media

United States
Environmental Protection
Agency

Office of Policy, Planning,
and Evaluation
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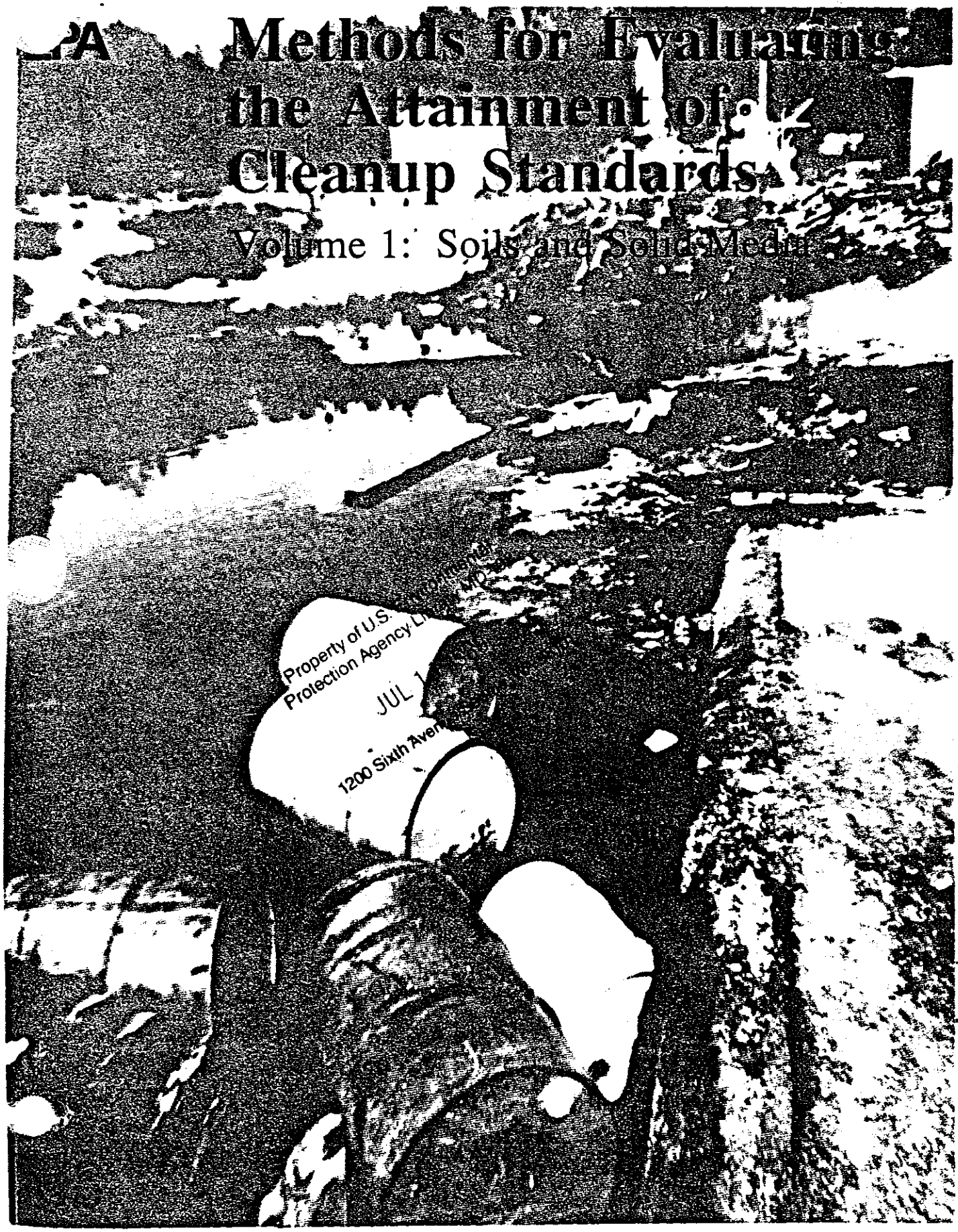
February 1989

Methods for Evaluating the Attainment of Cleanup Standards

Volume 1: Soils and Solid Media



4. DESIGN OF THE SAMPLING AND ANALYSIS PLAN

Once the attainment objectives are specified by program and subject matter personnel, statisticians can be useful for designing important components of sampling and analysis plans.

The methods of analysis must be consistent with the sample design and the attainment objectives. For example, data that are collected using stratified sampling cannot be analyzed using the equations for simple random sampling. The sample design and analysis plan must coincide. If there appears to be any reason to use different sample designs or analysis plans than those discussed in this manual, or if there is any reason to change either the sample design or the analysis plan after field data collection has started, it is recommended that a statistician be consulted.

This chapter presents some approaches to the design of a sampling and analysis plan and presents the strengths and weaknesses of various designs.

4.1 The Sampling Plan

The following sections provide background discussion guiding the choice of sampling plan for each sampling area. Chapter 5 discusses the details of how to implement a sampling plan. For more details, see Kish (1965), Cochran (1977), Hansen et al. (1953), or the EPA guidances in Table 1.1.

The sample designs considered in this document are:

- Simple random sampling called **random sampling** in this document;
- Stratified random sampling called **stratified sampling** in this document;
- Simple systematic sampling called **systematic sampling** in this document; and

- Sequential random sampling called **sequential sampling** in this document.

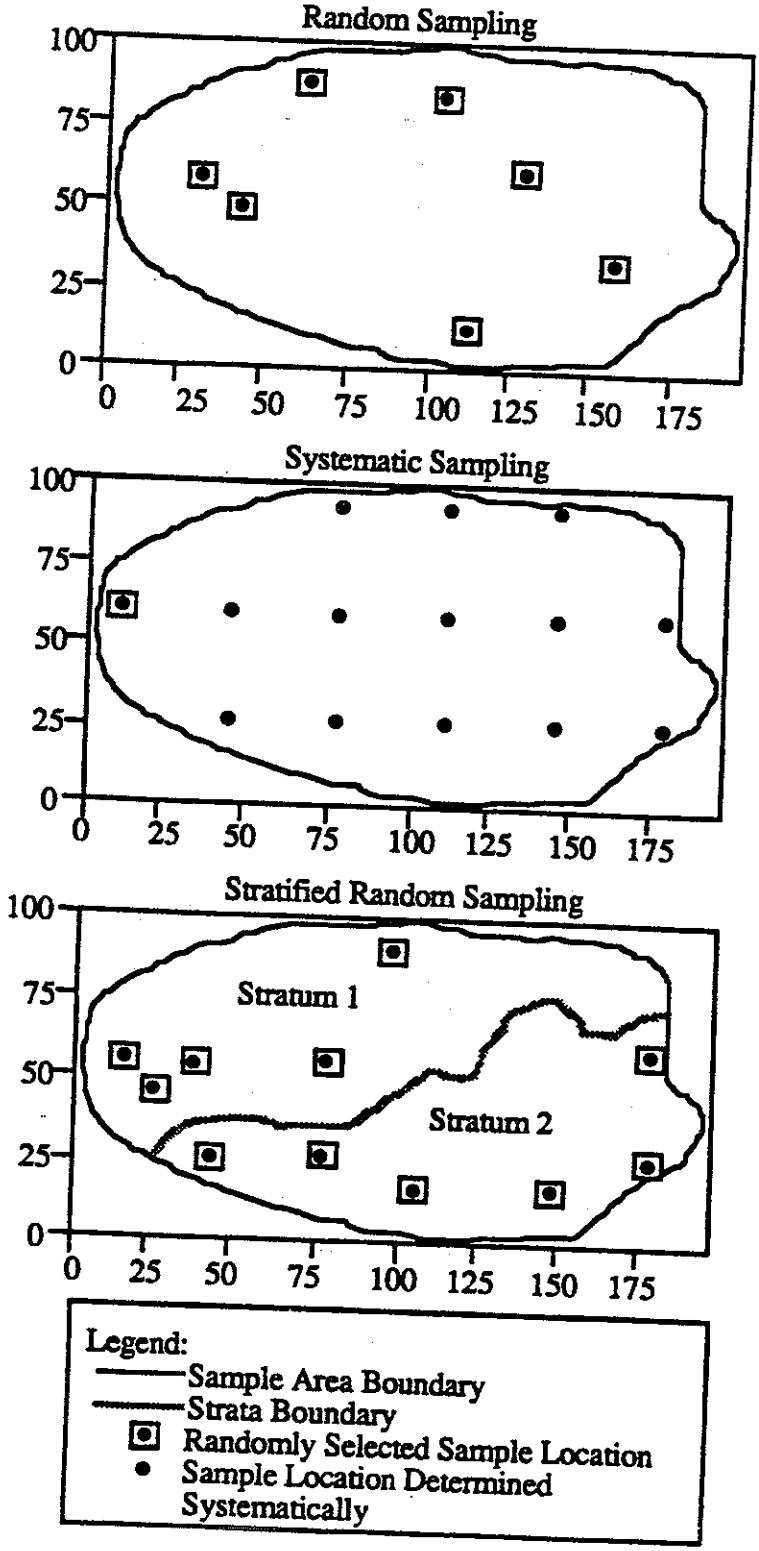
Randomization is necessary to make probability or confidence statements about the results of the sampling. Both random and random start systematic sample locations have random components. In contrast, sample selection using the judgment of the sampler has no randomization. Results from such samples cannot be generalized to the whole sample area and no probability statements can be made when judgment sampling is used. Judgment sampling may be justified, for example, during the preliminary assessment and site investigation stages if the sampler has substantial knowledge of the sources and history of contamination. However, judgment samples should not be used to determine whether the cleanup standard has been attained.

Combinations of the designs referred to above can also be used. For example, systematic sampling could be used with stratified sampling. In the situation where cleanup has occurred, if the concentrations across the site are relatively low and uniform and the site is accessible, the sample designs considered in this document should be adequate. If other more complicated sample designs are necessary, it is recommended that a statistician be consulted on the best design, and on the appropriate analysis method for that design. Figure 4.1 illustrates a random, systematic, and stratified sample.

4.1.1 Random Versus Systematic Sampling

Random selection of sample points requires that each sample point be selected independent of the location of all other sample points. Figure 4.1 shows a random sample. Note that under random sampling no pattern is expected in the distribution of the points. However, it is possible (purely by chance) that all of the sample points will be clustered in, say, one or two quadrants of the site. This possibility is extremely small for larger sample sizes.

Figure 4.1 Illustration of Random, Systematic, and Stratified Sampling (axes are distance in meters)



An alternative to random sampling is systematic sampling, which distributes the sample more uniformly over the site. Because the sample points follow a simple pattern and are separated by a fixed distance, locating the sample points in the field may be easier using a systematic sample than using a random sample. In many circumstances, estimates from systematic sampling may be preferred. More discussion of systematic versus random sampling can be found in Finney (1948), Legg, et al. (1985), Cochran (1977), Osborne (1942), Palley and Horwitz (1961), Peshkova (1970), and Wolter (1984).

4.1.2 Simple Versus Stratified Sampling

The precision of statistical estimates may be improved by dividing a sample area into more homogeneous strata. In this way, the variability due to soil, location, characteristics of the terrain, etc. can be controlled, thereby improving the precision of contamination level estimates. Homogeneous areas from which separate samples are drawn are referred to as "strata," and the combined sample from all areas is referred to as a "stratified sample."

Like systematic sampling, stratification provides another way of minimizing the possibility that important areas of the site will not be represented in the sample. Note in Figure 4.1 that the two strata represent subareas for which representation in the sample will be guaranteed under a stratified sampling design.

The main advantage of stratification is that it can result in a more efficient allocation of resources than would be possible with a simple random sample. For example, suppose that, based on physical features, the site can be divided into a hilly and a flat area, and that the hilly area comprises about 75 percent of the total area and is more expensive to sample than the flat area. If there is no reason to analyze the two subareas separately, we might consider selecting a simple random sample of soil units across the entire site. However, with a simple random sample, about 75 percent of the sample would be in the hilly, and therefore more expensive, areas of the site. With stratified sampling, the sample can be allocated disproportionately to the two subareas, i.e., sample fewer units from hilly areas and more from flat areas. In this way, the resulting cost savings (over a simple random sample) can be used to increase the total sample size and, hence, the precision of estimates from the sample.

The above illustration is highly simplified. In addition to differential stratum costs, factors such as the relative sizes of the strata and the variability of the contaminant under study in the different strata will affect the optimum allocation. The illustration does, however, point out that stratification can be used to design a more efficient sample, and is more than simply a device to ensure that particular subareas of the site are represented in the sample. A formal discussion of stratified sampling, and the cost and variance considerations used to determine an optimum allocation, is beyond the scope of this manual. However, sections 5.4 and 6.4 offer a discussion of the basic principles used to guide the design of a stratified sample.

Although stratified sampling is more difficult to implement in the field and slightly more difficult to analyze, stratified sampling will provide benefits if differences in mean concentrations or sampling costs across the sample area exist and can be reasonably identified using available data. It is important to define strata so that the physical samples within a stratum are more similar to each other than to samples from different strata. Factors that can be used to define strata are:

- Sampling depth (see section 5.6 for details);
- Concentration level;
- Physiography/topography;
- The presence of other contaminants that affect the analytical techniques required at the lab;
- The history and sources of contamination over the site;
- Previous cleanup attempts; or
- Weathering and run-off processes.

There are two fundamental and important points to remember when defining areas that will become different strata:

- The strata must not overlap--no area within one strata can be within another strata; and
- The sum of the sizes of the strata must equal the area of the sample area.

In other words, the strata must collectively account for the entire sample area of interest--no more, no less.

4.1.3 Sequential Sampling

For most statistical methods, the analysis is performed after the entire sample has been collected and the laboratory results are complete. In sequential random sampling, the samples are analyzed as they are collected. A statistical analysis of the data, after each sample is collected and analyzed, is used to determine if another sample is to be collected or if the sampling program terminates with a decision that the site is clean or dirty. (Sequential sampling is the subject of Chapter 8.)

4.2 The Analysis Plan

Similar to sampling plan designs, planning an approach to analysis and the actual analysis begin before the first sample is collected. The first task of the analysis plan is to determine how the cleanup standard should function. In other words, what is the cleanup standard: a value that should be rarely exceeded; an average value; or a level that defines the presence of a hot spot? This must be decided because it determines what analysis method will be used to determine attainment.

Second, the analysis plan must be developed in conjunction with the sampling plan discussed earlier in this chapter. For example, plans to conduct stratified sampling cannot be analyzed using the equations for random sampling.

Third, the first actual step required in the analysis plan should be a determination of the appropriate sample size. This requires calculations and evaluation before the data are collected. Often the number of samples is determined by economics and budget rather than an evaluation of the required accuracy. Nevertheless, it is important to evaluate the accuracy associated with a prespecified number of samples.

Fourth, the analysis plan will describe the evaluation of the resulting data. Chapters 6 through 10 offer various analytical approaches, depending on attainment objectives and the sampling program. Table 4.1 presents where in this document various combinations of analysis and sampling plans are discussed.

Table 4.1 Where sample designs and analysis methods for soil sampling are discussed in this document

Type of Evaluation	Analysis Method	Chapter Location: Sample Design			
		Random	Stratified	Systematic	Sequential
Test of the Mean	Test for means	6.3.3	6.4.2	6.5.2	
Test of Percentiles	Nonparametric Tolerance Intervals	7.3.3 7.3.6	7.5.2	7.6	
	Sequential Sampling				8.2
Hot Spot Evaluation				9.2.1	
Geostatistics	Indicator Kriging			10.3	

4.3 Summary

Design of the sampling and analysis plan requires specification of attainment objectives by program and subject matter personnel. The sampling and analysis objectives can be refined with the assistance of statistical expertise. The sample design and analysis plans go together; therefore, the following methods of analysis must be consistent with the sample design:

- Random sampling;
- Stratified sampling;

- Systematic sampling; and
- Sequential sampling.

Random selection of sample points requires that each sample point be selected independent of the location of all other sample points. An alternative to random sampling is systematic sampling, which distributes the sample more uniformly over the site. Systematic sampling is preferred in hot spot searches and in geostatistical studies.

Like systematic sampling, stratified sampling minimizes the possibility that important areas of the site will not be represented by dividing a sample area into homogeneous subareas. The main advantage of stratification is that it can result in a more efficient allocation of resources than would be possible with a random sample.

Sequential sampling (Chapter 8) requires that the samples be analyzed as they are collected.

Decisions required to plan an approach to analysis are:

- Determine the analysis method that is most useful;
- Develop the plan in conjunction with the sampling plan;
- Determine the appropriate sample size; and
- Describe how the resulting data will be evaluated.

5. FIELD SAMPLING PROCEDURES

The procedures discussed in this chapter ensure that:

- The method of establishing soil sample locations in the field is consistent with the planned sample design;
- Each sample location is selected in a nonjudgmental and unbiased way; and
- Complete documentation of all sampling steps is maintained.

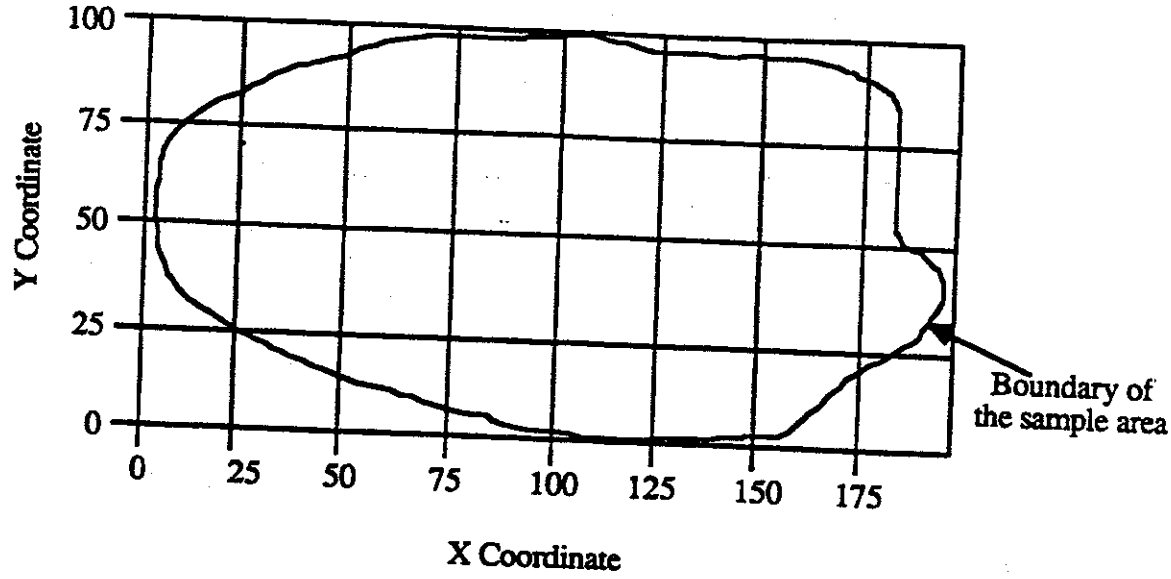
The procedures discussed in this chapter assume that the sampling plan has been selected; the boundaries of the waste site, the sample areas, and any strata have been defined; a detailed map of the waste site is available; and the sample size is known. Sample size determination is discussed in Chapters 6, 7, 8, and 9. Also, if sequential sampling or hot spot searches are planned, the reader should refer to Chapters 8 and 9, respectively, for additional guidance on field sampling.

5.1 Determining the General Sampling Location

Locating the soil samples is accomplished using a detailed map of the waste site with a coordinate system to identify sampling locations. Recording and automation of station-specific data should retain coordinate information, especially if geostatistical manipulations are performed (see Chapter 10) or a geographic information system will be used.

Soil sample locations will be identified by X and Y coordinates within the grid system. It is not necessary to draw a grid for the entire waste site; it is only necessary to identify the actual coordinates selected. Figure 5.1 is an example of a map with a coordinate system. In this example, the origin of the coordinate system is at the lower lefthand corner of the map; however, this may not be true for coordinate systems based on measurements from a reference point on the ground, i.e., a benchmark or a standard coordinate system such as latitude and longitude.

Figure 5.1 Map of a Sample Area with a Coordinate System



The boundaries of the sample areas (areas within the site for which separate attainment decisions are to be made) and strata within the sample areas (if stratified sampling is required) should be shown on the map. The map should also include other important features that will be useful in identifying sample locations in the field.

Accurate location of sampling points can be expensive and time consuming. Therefore, a method is suggested which uses the coordinate system to identify the general area within which the soil sample is to be collected, followed by a second stage of sampling, described in section 5.5, to identify the sample point accurately.

The X and Y coordinates of each sample location must be specified. This distance between coordinates on each axis represents a reasonable accuracy for measuring distance in the field, and is represented by M. If distances can be measured easily to within 2 m, but not to within 1 meter, the coordinates should be provided to the nearest 2 m (M = 2 m). The sampling coordinates can be identified with greater accuracy when the distances to be measured between reference points are short, the measuring equipment is accurate or easy to use, or there are few obstructions to line-of-sight measuring such as hills, trees, or bushy vegetation. For example, the location within a small lagoon, say, 30 by 30 m, can

be established to within 5 cm. On the other hand, in a 10 hectare field it may only be reasonable to identify a location to within 10 m.

5.2 Selecting the Sample Coordinates for a Simple Random Sample

A random sample of soil units within the sample area or stratum will be selected by generating a series of random (X,Y) coordinates, finding the location in the field associated with these (X,Y) coordinates, and following the field procedures described in section 5.5 for collecting soil samples. If the waste site contains multiple sample areas and/or strata, the same procedure described above is used to generate random pairs of coordinates with the appropriate range until the specified sample size for the particular portion of the site has been met. In other words, a separate simple random sample of locations should be drawn for each sample area or stratum. To simplify the discussion, the procedures below discuss selection of a random sample in a sample area.

The number of soil samples to be collected must be specified for each sample area. In what follows, the term n_f will be used to denote the number of samples to be collected in the sample area.

To generate the n_f random coordinates (X_i,Y_i), $i = 1$ to n_f, for the sample area, determine the range of X and Y coordinates that will completely cover the sample area. These coordinate ranges will define a rectangle that circumscribes the sample area. Let the coordinate ranges be X_{min} to X_{max} and Y_{min} to Y_{max}. Thus, the point (X_{min}, Y_{min}) represents the lower lefthand corner of the rectangle, and (X_{max}, Y_{max}) represents the upper righthand corner of the rectangle. The n_f sample coordinates (X_i,Y_i) can be generated using a random number generator and the steps described in Box 5.1. Box 5.2 gives an example of generating random sample locations.

Box 5.1
Steps for Generating Random Coordinates That Define Sampling Locations

1) Generate a set of coordinates (X,Y) using the following equations:

$$X = X_{min} + (X_{max} - X_{min})*RND \qquad (5.1)$$

$$Y = Y_{min} + (Y_{max} - Y_{min})*RND \qquad (5.2)$$

RND is the next unused random number between 0 and 1 in a sequence of random numbers. Random numbers can be obtained from calculators, computer software, or tables of random numbers.

2) If (X,Y) is outside the sample area, return to step 1 to generate another random coordinate; otherwise go to step 3.

3) Define (X_i,Y_i) using the following steps:

Round X to the nearest unit that can be located easily in the field (see section 5.1); set this equal to X_i

Round Y to the nearest unit that can be located easily in the field (see section 5.1); set this equal to Y_i.

4) Continue to generate the next random coordinate, (X_{i+1},Y_{i+1}).

Box 5.2
An Example of Generating Random Sampling Locations

To illustrate the selection of simple random sample of locations, assume that seven soil units will be selected from the site in Figure 5.2. Pairs of random numbers (one X coordinate and Y coordinate for each pair) identify each sample point. X will be measured on the map's coordinate system in the horizontal direction and Y in the vertical direction. It is assumed for this example that selected coordinates can be identified to the nearest meter. The first number of pair, X_i, must be between 0 and 190 (i.e., $X_{min} = 0$ and $X_{max} = 190$) and the second, Y_i, between 0 and 100 ($Y_{min} = 0$ and $Y_{max} = 100$) for this example. If the X and Y coordinates for any pair identify a location outside the area of interest, they are ignored and the process is continued until the sample size n_f has been achieved.

X Y pair	Random X coordinate	Random Y coordinate
1	67	80
2	97	4
3	190	88 (outside of sample area)
4	17	15 (outside of sample area)
5	94	76
6	123	49
7	25	52
8	35	39
9	152	14

It took nine attempts to secure seven coordinates that fall within the sample area. The randomly selected coordinates for pairs 3 and 4 fall outside the waste site and are to be discarded. The remaining seven locations are randomly distributed throughout the site.

These locations can now be plotted on the map, as shown in Figure 5.2.

5.3 Selecting the Sample Coordinates for a Systematic Sample

A square grid and a triangular grid are two common patterns used in systematic or grid sampling. These patterns are shown in Figure 5.3. Note that the rows of points in the triangular grid are closer (.866L) than the distance between points in a row (L) and that the points in every other row are offset by half a grid width.

Figure 5.2 Map of a Sample Area Showing Random Sampling Locations

Locations of the random samples are indicated by a •. The numbers reference the XY pairs in Box 5.2.

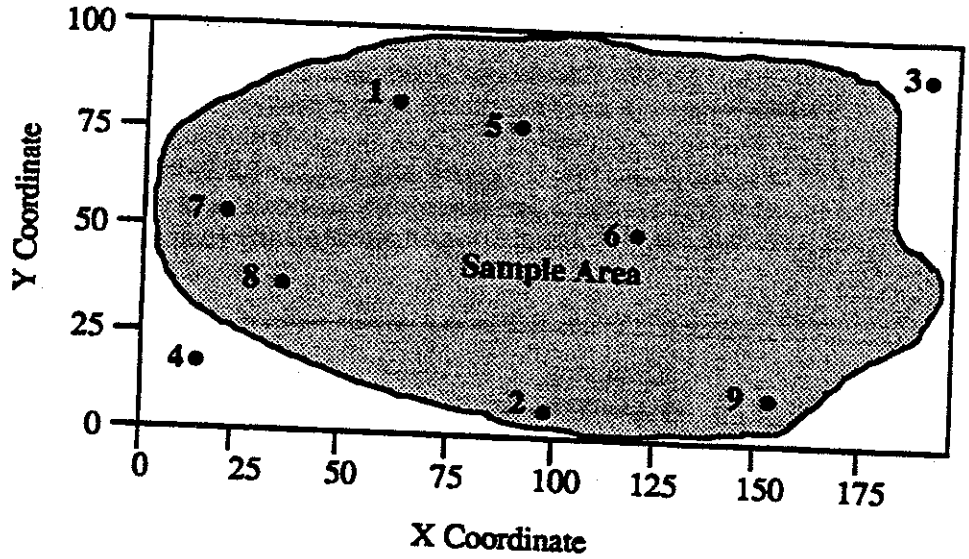
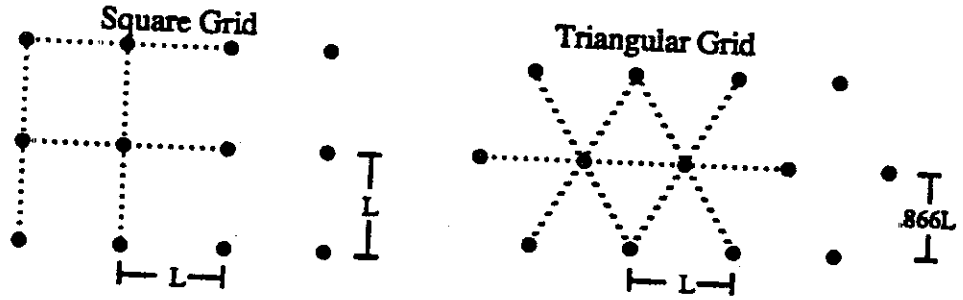


Figure 5.3 Examples of a Square and a Triangular Grid for Systematic Sampling



The size of the sample area must be determined in order to calculate the distance, L, between the sampling locations in the systematic grid. The area can be measured on a map using a planimeter. The units of the area measurement (such as square feet, hectares, square meters) should be recorded.

Denote the surface area of the sample area by A. Use the equations in Box 5.3 to calculate the spacing between adjacent sampling locations.

Box 5.3
Calculating Spacing Between Adjacent Sampling Locations

for the Square Grid in Figure 5.3

$$L = \sqrt{\frac{A}{n_f}} \qquad (5.3)$$

for the Triangular Grid in Figure 5.3

$$L = \sqrt{\frac{A}{.866 n_f}} \qquad (5.4)$$

The distance between adjacent points, L, should be rounded to the nearest unit that can be easily measured in the field.

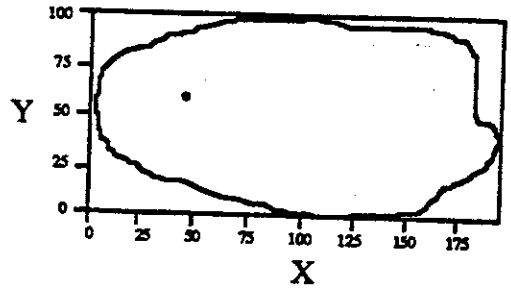
After computing L, the actual location of one point in the grid should be chosen by a random procedure. First, select a random coordinate (X,Y) following the procedure in Box 5.1. Using this location as one intersection of two gridlines, construct gridlines running parallel to the coordinate axes and separated by a distance L. The sampling locations are the points at the intersections of the gridlines that are within the sample area boundaries. Figure 5.4 illustrates this procedure. Using this procedure, the grid will always be oriented parallel to the coordinate axes. The grid intersections that lie outside the sample area are ignored. There will be some variation in sample size, depending on the location of the initial randomly drawn point. However, the relative variation in number of sample points becomes small as the number of desired sample points increases. For unusually shaped sample areas (or strata), the number of sample points can vary considerably from the desired number.

The coordinates for the sample points will be all coordinates (X_i, Y_i) such that:

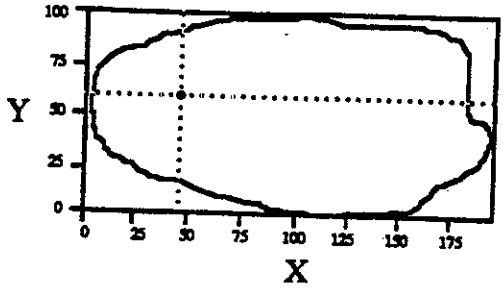
- (X_i, Y_i) is inside the sample area or stratum;
- $X_i = X + j*L$, for some positive or negative integer j, and;
- $Y_i = Y + k*L$, for some positive or negative integer k.

Figure 5.4 Locating a Square Grid Systematic Sample

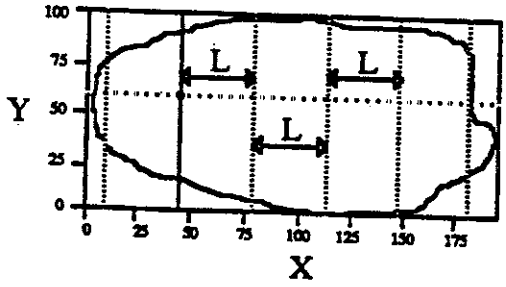
(1) Select initial random point.



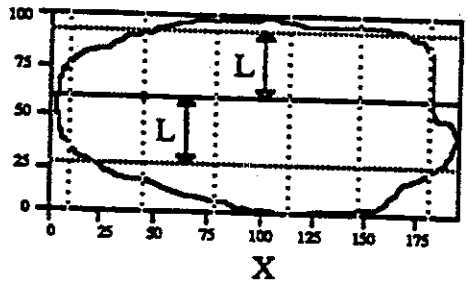
(2) Construct coordinate axis going through initial point.



(3) Construct lines parallel to vertical axis, separated by a distance of L.



(4) Construct lines parallel to horizontal axis, separated by a distance of L.



Box 5.4 and Figure 5.5 give an example of locating systematic coordinates and the resultant sampling locations plotted on a map of the site.

Box 5.4
Locating Systematic Coordinates

Using the map in Figure 5.1 and a planimeter, the area of the sample area is determined to be 14,025 sq. m. If the sample size is 12, the spacing between adjacent points is:

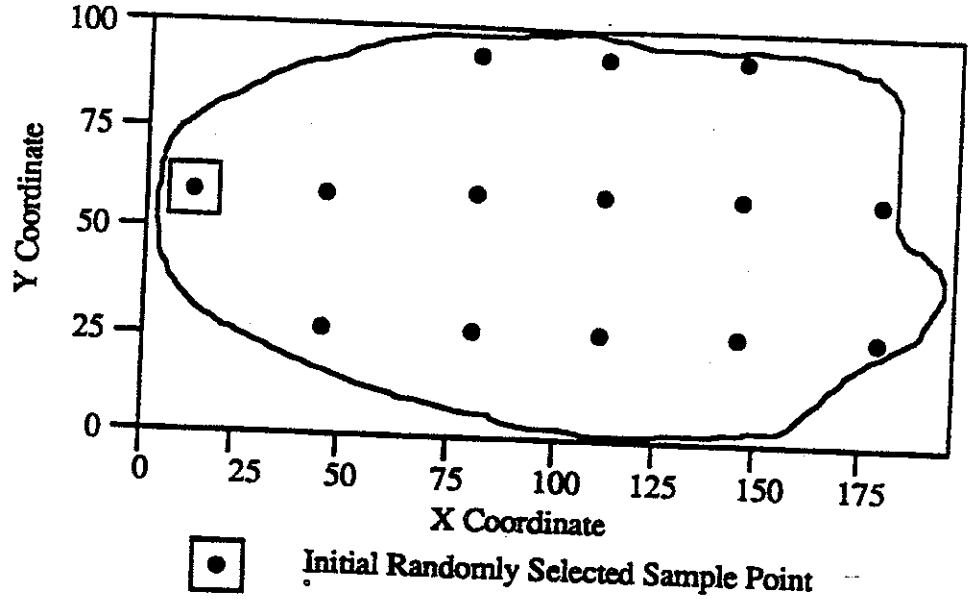
$$L = \sqrt{\frac{A}{n_f}} = \sqrt{\frac{14025}{12}} = 34 \text{ m, rounded to the nearest meter}$$

Using the procedure in Box 5.1, a random coordinate (X,Y) = (11,60) is generated. Starting from this point, the following sampling points can be calculated:

		(79,94)	(113,94)	(147,94)	
(11,60)	(45,60)	(79,60)	(113,60)	(147,60)	(181,60)
	(45,26)	(79,26)	(113,26)	(147,26)	(181,26)

These points are shown in Figure 5.5. The intended sample size was 12; however, because of the random selection process and the irregularity of the sample area boundary, there are 14 sample points within the sample area. A sample will be collected at all 14 locations.

Figure 5.5 Map of a Sample Site Showing Systematic Sampling Locations



5.3.1 An Alternative Method for Locating the Random Start Position for a Systematic Sample

An alternative method may be used to locate the random start position for a systematic triangular grid sample (J. Barich, Pers. Com., 1988). This approach, as detailed in Box 5.5, determines a random start location by choosing a random angle A and a random distance Y from point X. This approach is useful under circumstances where a transit and stadia rod are available for turning angles, measuring distances, and establishing transects. This method is essentially equivalent to the method described above.

Box 5.5
Alternative Method for Locating the Random Start Position for a Systematic Sample

Figure 5.6 and the following steps explain how to implement the sequence.

1) Establish the main transect with endpoints X and X' using any convenient reference line (e.g., established boundary). Notice that the transect X-X' must be longer than the line indicated in Figure 5.6 in order to site all of the transects that intersect the sample area.

2) Randomly choose a point Y between X and X'.

3) Randomly choose an angle A between 0° and 90°.

4) Locate transect with endpoints Y and Y', A degrees from transect X and X'. If this transect intersects the boundary of the sample area, mark the transect.

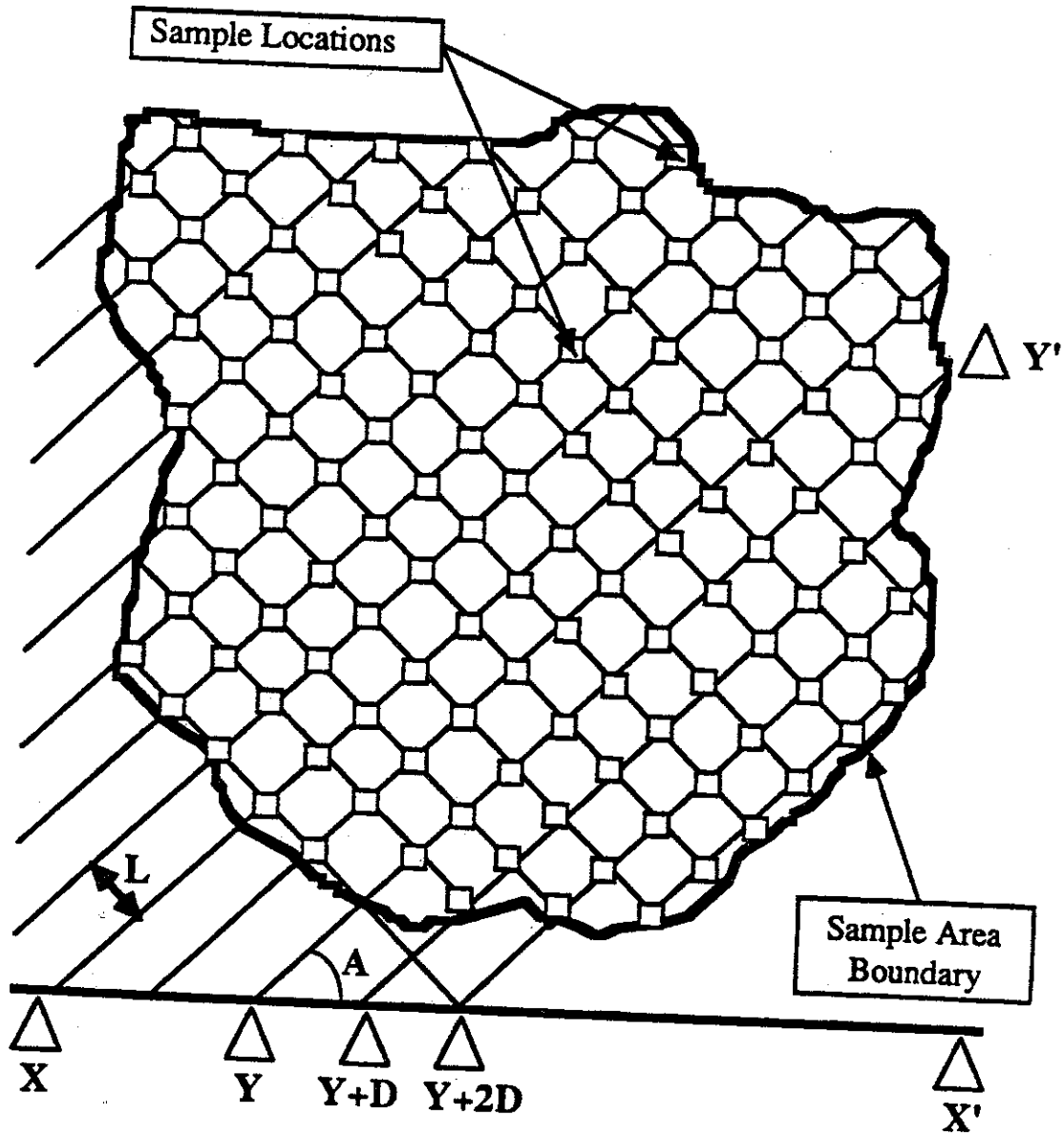
5) Locate another transect beginning at point Y and 90° +A (i.e., perpendicular) from that transect that intersects the boundary of the sample area; then mark the transect Y-Y'. If this transect intersects the boundary of the sample area then mark the transect.

6) Move away from point Y on transect X-X' a distance D, where $D=L/\sin(A)$. L is the desired interval between sampling points along the grid pattern.

7) At the point D units away from Y, establish two more transects: one A degrees from transect X-X' and parallel to transect Y-Y', and the other 90°+A degrees from X-X' also beginning at the point D units from point Y.

8) Continue to move intervals of distance D along the transect X-X' until two transects intersect within the boundary of the sample area. Establish the first sample location at that point. Then measure along that transect from the first sampling location a distance of L and establish more transects and grid points using the approach described in the previous method for systematic samples.

Figure 5.6 Method for Positioning Systematic Sample Locations in the Field



Where **D = L/sin A**

Y is chosen randomly
A is chosen randomly
L is determined from sample size calculations
□ is a physical sampling location

5.4 Extension to Stratified Sampling

The extension of these procedures to stratified sampling is straightforward. Each stratum is sampled separately using the methods discussed above. Different random sequences (or random numbers for locating the grids) should be used in each stratum within the sample area. The sampling approach chosen for one stratum does not have to be used in another stratum. For example, if a sample area is made up of a small waste pile and a large 200-acre hillside, then it would be possible to use systematic sampling for the hillside and random sampling for the waste pile.

5.5 Field Procedures for Determining the Exact Sampling Location

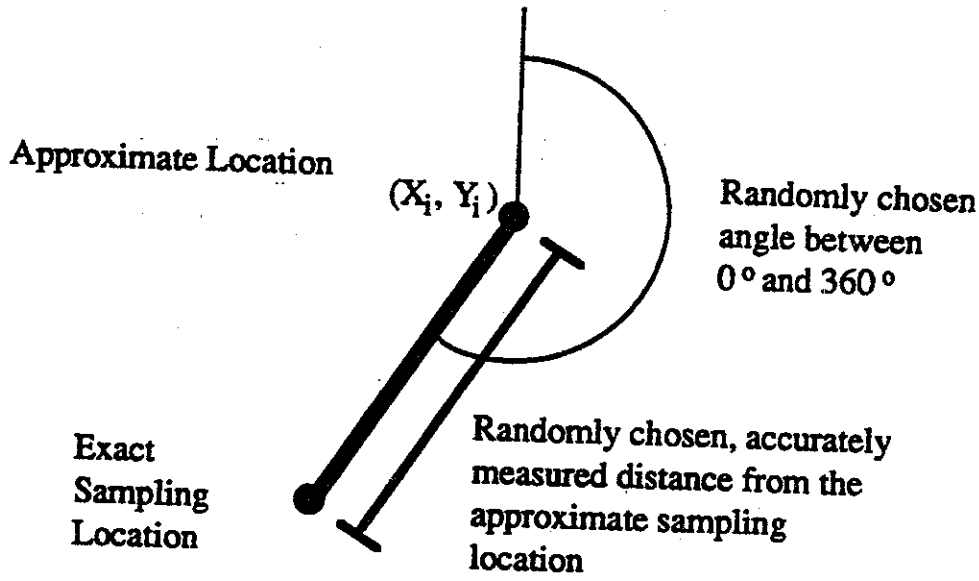
The grid points specified for the coordinate system or other reference points (e.g., trees, boulders, or other landmarks) provide the starting point for locating the sample points in the field. The location of a sample point in the field will be approximate because the sampling coordinates were rounded to distances that are easy to measure, the measurement has some inaccuracies, and there is judgment on the part of the field staff in locating the sample point.

A procedure to locate the exact sample collection point is recommended to avoid subjective factors that may affect the results. Without this precaution, subtle factors such as the difficulty in collecting a sample, the presence of vegetation, or the color of the soil may affect where the sample is taken, and thus bias the results.

To locate the exact sample collection point in the field, use one of the following procedures (or a similar procedure) to move from the location identified when measuring from the reference points to the final sample collection point. In the methods below, M is the accuracy to which distances can be easily measured in the field.

- Choose a random compass direction (0 to 360 degrees or N, NE, E, SE, etc.) and a random distance (from zero to M meters) to go to the sample location (as illustrated in Figure 5.7).
- Choose a random distance (from -M meters to M meters) to go in the X direction and a random distance (from -M meters to M meters) to go in the Y direction, based on the coordinate system.

Figure 5.7 An Example Illustration of How to Choose an Exact Field Sampling Location from an Approximate Location



For either of these procedures, the random numbers can be generated in the field using a hand-held calculator or by generating the random numbers prior to sampling. The sample should be collected as close to this exact sampling location as possible.

5.6 Subsampling and Sampling Across Depth

Methods for deciding how and where to subsample a soil core are important to understand and include in a sampling plan. These methods should be executed consistently throughout the site. The field methods that are used will depend on many things including the soil sampling device, the quantity of material needed for analysis, the contaminants that are present, and the consistency of the solid or soils media that is being sampled. The details of how these considerations influence field procedures are not the subject of this discussion, but they are important and related to the discussion. More detail can be obtained in the Soil Sampling Quality Assurance User's Guide (USEPA, 1984).

This discussion describes methods for soil acquisition across depth once an exact auguring or coring position has been determined and describes how these approaches

influence the interpretation of sampling results. There are several approaches that might be considered each with advantages and disadvantages; these are outlined in Figure 5.8.

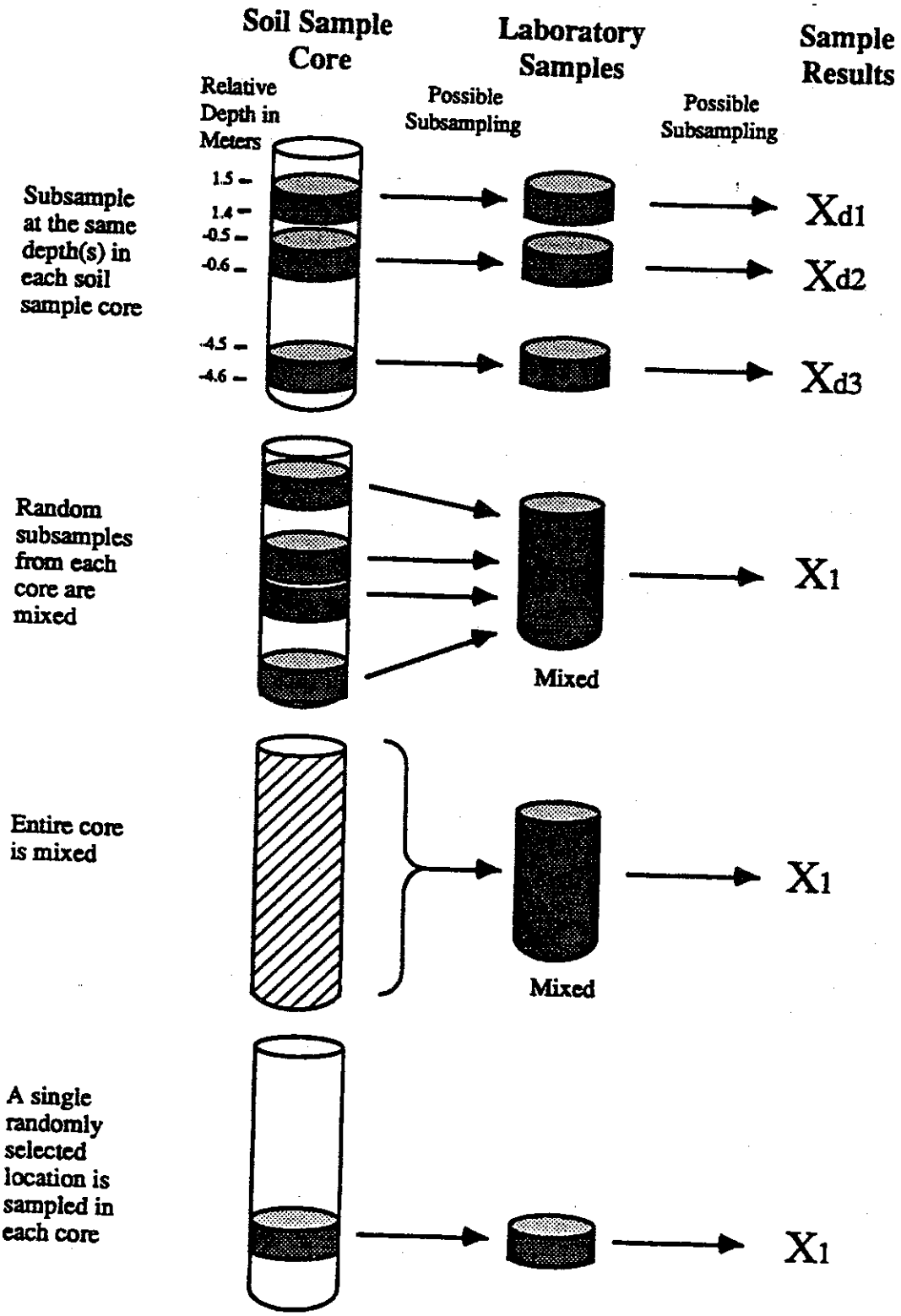
5.6.1 Depth Discrete Sampling

The first approach is to decide before sampling on an exact position or positions across depth that will be retained for analysis. For example, it may be decided that throughout the site a split spoon will be driven so that the soil within the following intervals is retained and sent to the laboratory for separate analysis: at elevations 1.5 m to 1.4 m, -0.5m to -0.6 m, and -4.5 m to -4.6 m (relative to a geodetic or site standard elevation). The size of the interval would depend on the volume required by the laboratory. In this example, all the soils material within each interval is extracted and analyzed. Advantages of this approach are that each depth can be considered a different sample area and conclusions regarding the attainment of cleanup standards can be made independently for each soil horizon. This is also a preferred method when the presence of volatiles in the soils media prevents the application of compositing methods.

5.6.2 Compositing Across Depth

Other approaches to sample acquisition within a core are based on compositing methods. Compositing methods are generally to be approached with caution unless the statistical parameter of interest is the mean concentration. If the mean is the statistic of interest, then the variance of the mean contributed by differences in location across the site from composited samples will be lower than the same variance associated with the mean from noncomposited samples. However, compositing will restrict the evaluation of the proportion of soil above an established cleanup standard because of the physical averaging that occurs in the compositing process. Clearly compositing is not recommended if the compositing process will influence the mass of material in the sample as in the case of volatile organics within a soils matrix. Numerous authors have contributed to the understanding of the effects of compositing (Duncan, 1962; Elder et al., 1980; Rohde, 1976; Schaeffer and Janardan, 1978; and Schaeffer et al., 1980), and these references or a statistician should be consulted if complicated compositing strategies are planned.

Figure 5.8 Subsampling and Sampling Across Depth



Under one compositing method, segments of the soil core are retained from randomly or systematically identified locations. Then only the sampled portions are homogenized and then subsampled. Another approach calls for retaining the entire core and homogenizing all of the material and then subsampling. The latter approach is preferred from a statistical point of view because the subsampling variance will be lower. However, the second method may present difficulties if the soil samples are obtained to considerable depth or by split spoon. In these situations, it is clearly not reasonable or cost effective to acquire a core from the entire soil profile. On the other hand, if a hand-held core or continuous coring device such as a vibra-corer is being used, then homogenization of the entire core may be possible. In general, large amounts of material, material that is difficult to manipulate because of its physical properties, material containing analytes that will volatilize, or hazardous soil make thorough mixing more difficult, which may eventually defeat the positive features associated with homogenization of the entire core.

5.6.3 Random Sampling Across Depth

A final approach involves randomly sampling a single location within each core. At first, this approach appears to have many difficulties, but if the interest is in verifying that the proportion of soil above a cleanup standard is low, this approach will work quite well.

Suppose that an in situ soils stabilization method was used to treat all of the overburden soils within a former lagoon. The treatment was previously found to yield effective and homogeneous results over depth and space. It would clearly not be appropriate to sample at a single depth of, say, 3m. Since depth homogeneity is expected, it may also not be necessary to evaluate several specific depths by sampling 1-m, 3-m, 7-m, and 15-m horizons in each boring. Finally and most importantly, it would not be recommended to perform compositing because the statistical parameter of interest is the proportion of soil at the site above the cleanup standard and not the mean concentration.

In this situation it may be useful to pick a random depth at each location. In this way, many depths will be represented across the lagoon. Also, cost may be reduced

because at many locations the auger will not have to drill to bedrock because the sample will be obtained from a random location that, in some samples, will be near the surface.

5.7 Quality Assurance/Quality Control (QA/QC) in Handling the Sample During and After Collection

Data resulting from a sampling program can only be evaluated and interpreted with confidence when adequate quality assurance methods and procedures have been incorporated into the design. An adequate quality assurance program requires awareness of the sources of error associated with each step of the sampling effort.

A full discussion of this topic is beyond the scope of the document; however, the implementation of a QA program is important. For additional details, see *Soil Sampling Quality Assurance User's Guide* (USEPA, 1984), Brown and Black (1983), and Garner (1985).

5.8 Summary

Locating soil samples is accomplished using a detailed map of the waste site with a coordinate system to identify sampling locations. The boundaries of the sample areas (areas within the site for which separate cleanup verification decisions are to be made) and strata within the sample areas should be shown on the map. It is not necessary to draw a grid for the entire waste site, only to identify the actual coordinates selected.

A random sample of soil units within the sample area or stratum will be selected by generating a series of random (X,Y) coordinates and identifying the location associated with these coordinates.

When selecting the sample coordinates for a systematic sample, two common patterns of systematic or grid samples are a square grid and a triangular grid. Various methods can be used to select a systematic sample; however, the most important point is that one of the systematic sample locations must be identified randomly.

A separate random or systematic sample is selected for each sample area. In addition, the extension of these procedures to stratified sampling is straightforward. Each stratum is sampled separately. The sampling approach chosen for one stratum, or sample area does not have to be used in another stratum.

Once a horizontal position is chosen, the method of acquiring samples across depth must be decided. Methods for subsampling and sampling across depth should be executed consistently throughout the site. The methods discussed are:

- Depth discrete sampling;
- Compositing across depth; and
- Random sampling across depth.

9. SEARCHING FOR HOT SPOTS

As suggested by Barth et al. (1989), it may be desirable to verify cleanups by documenting that no hot spots could be identified provided that a sampling plan was used that had an acceptably large probability of finding hot spots. This chapter discusses how to conduct a valid sampling program to search for hot spots and the conclusions that can be drawn regarding the presence or absence of hot spots. In general, the methods in this chapter are presented so they are easy to understand and apply.

This chapter first describes the literature that discusses methods for locating hot spots. This will provide the interested reader with an avenue into discussions regarding specific applications and details. A simple approach, useful under two different sampling designs, is summarized. This enables application of selected basic methods without having to obtain and study the literature.

9.1 Selected Literature that Describes Methods for Locating Hot Spots

Table 9.1 lists several references regarding hot spots and their identification. Gilbert (1987) offers a general overview of the hot spot searching technique, including example applications of the simplest methods as well as more advanced application. Zirschky and Gilbert (1984) offer applications of these methods at hazardous waste sites.

9.2 Sampling and Analysis Required to Search for Hot Spots

9.2.1 Basic Concepts

The term hot spot is used frequently in discussions regarding the sampling of hazardous waste sites, yet there is no universal definition of what constitutes a hot spot. The methods in this chapter model hot spots as localized elliptical areas with concentrations in excess of the cleanup standard. Hot spots are generally small relative to the area being sampled. The hot spot must either be considered a volume defined by the projection of the surface area through the soil zone that will be sampled or a discrete horizon within the soil

zone that will be sampled. When a sample is taken and the concentration of a chemical exceeds the cleanup standard for that chemical, it is concluded that the sampling position in the field was located within a hot spot.

Table 9.1 Selected references regarding the methodologies for identifying hot spots at waste sites

Gilbert, R.O. (1982)	Some Statistical Aspects of Finding Hot Spots and Buried Radioactivity
Gilbert, R.O. (1987)	Statistical Methods for Environmental Pollution Monitoring
Parkhurst, D.F. (1984)	Optimal Sampling Geometry for Hazardous Waste Sites
Singer, D.A. (1972)	Elipgrid: A Fortran IV Program for Calculating the Probability of Success in Locating Elliptical Targets with Square, Rectangular, and Hexagonal Grids
Singer, D.A. (1975)	Relative Efficiencies of Square and Triangular Grids in the Search for Elliptically Shaped Resource Targets
USEPA (1985)	Verification of PCB Spill Cleanup by Sampling and Analysis
Zirschky, J. and Gilbert, R.O. (1984)	Detecting Hot Spots at Hazardous Waste Sites

Hot spot location techniques involve systematic sampling from a grid of sampling points arranged in a particular pattern. If a systematic sample is taken and none of the samples yield concentrations in excess of the cleanup standard, then no hot spots were found and the site is judged clean. However, what does this mean in terms of the chances of contaminant residuals remaining at the site? Since all of the soil could not be sampled, hot spots could still be present. An important question is: What level of certainty is there that no hot spots exist at the site? The answer to this question requires that several other questions be answered. For example:

- What shape hot spot is of concern: circular, fat-elliptical, skinny-elliptical?
- What is the length of the longest axis of the hot spot : 1 cm, 10 m, or 100 m?
- What sampling pattern was used: square, triangular?
- What was the distance between sampling points in the grid: 0.1 m, 1 m, 100 m?

If these questions are answered; a sampling plan implemented; and no hot spots are found, it is possible to conclude with an associated level of confidence that no hot spots of a certain size are present. In general, there is a smaller chance of detecting hot spots and less confidence in conclusions when:

- Hot spot sizes of interest become smaller;
- Hot spots are likely to be narrow;
- A square rather than a triangular grid is used; and
- The spacing between grid points is increased.

Figure 9.1 illustrates a sampling grid with hot spots of various sizes and shapes. Hot spots B and D were "hit" with sampling points and hot spots A anc C were missed.

If one of the samples results in concentrations in excess of the applicable cleanup standard, a hot spot has been identified. The conclusion is that the site is not clean. The normal, reasonable action will be to continue remediation in the areas identified as hot spots. However, once these locations are remediated, another systematic sample, over the entire site, with a new random start must be taken in order to conclude with confidence that no hot spots of a specified size and shape are present at the site. Because of this requirement it may be advisable, after identifying the presence of a single hot spot, to continue less formal searching followed by treatment throughout the entire sample area.

9.2.2 Choice of a Sampling Plan

The sampling plan requires no calculations. Instead all the information is obtained from tables. Figure 9.2 describes the grid spacing definition for two grid configurations and how to calculate the parameter for defining the ellipse shape.

The sampling plan for hot spot detection can be approached in three ways. The three factors listed in Table 9.2 control the performance of a hot spot detection sampling episode. Two of these factors are chosen and fixed. The third factor is determined by the choice of the first two factors. Table A.11 includes information that allows choice of two factors while providing the resulting third parameter.

Figure 9.1 A Square Grid of Systematically Located Grid Points with Circular and Elliptical Hot Spots Superimposed

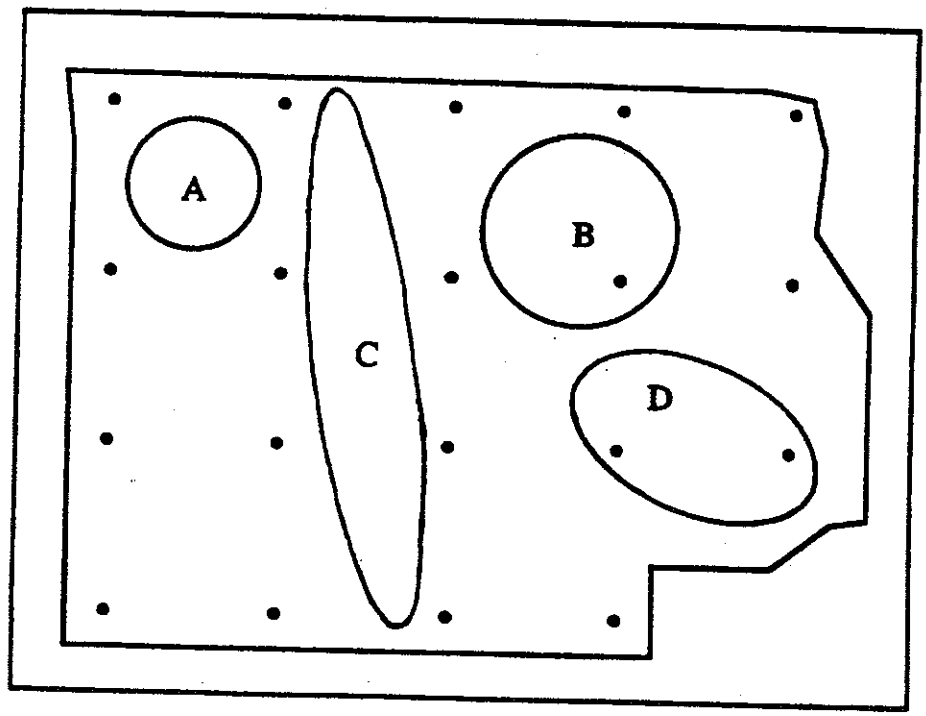
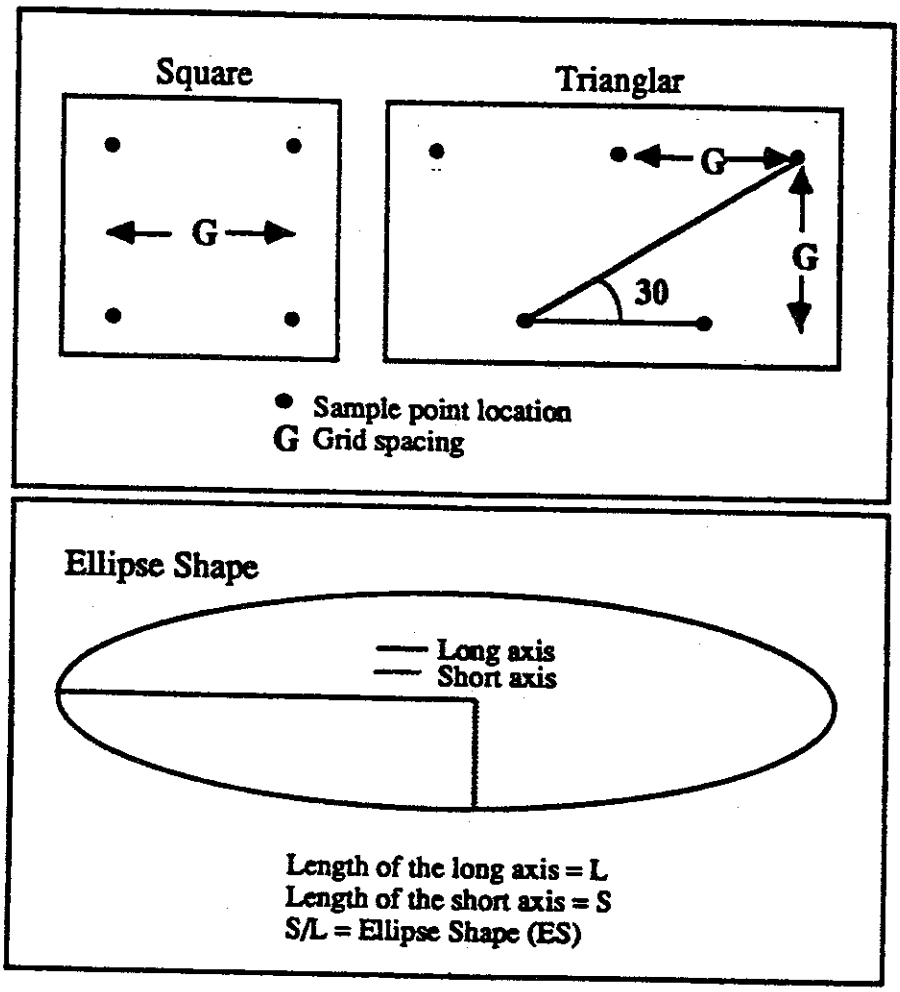


Figure 9.2 Grid Spacing and Ellipse Shape Definitions for the Hot Spot Search Table in Appendix A (Table A.11)



Selected Excerpts
from:

Methods for Evaluating the Attainment of Cleanup Standards.

Volume 2: Groundwater

United States
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Methods For Evaluating The Attainmen t Of Cleanup Standards

Volume 2: Ground Water

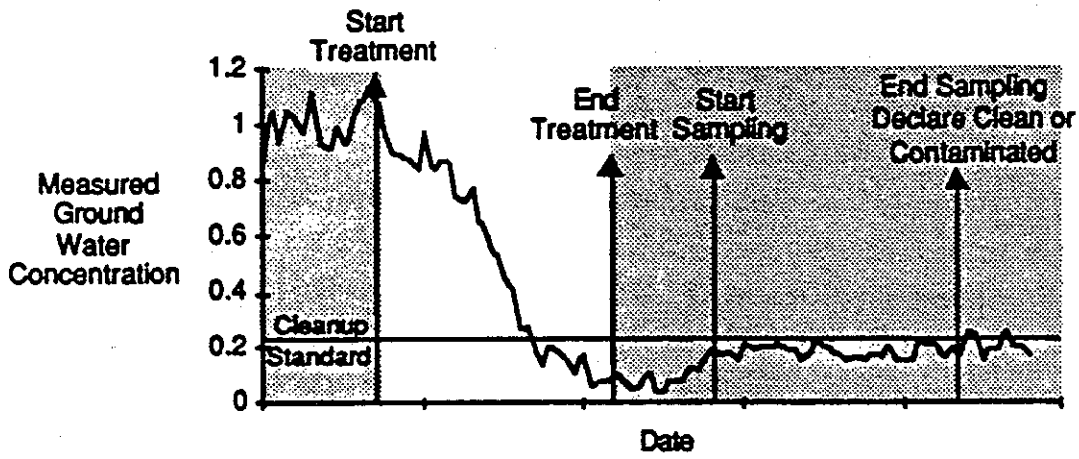
Statistical guidance for use in deciding when to end groundwater treatment.

See Appendix 1
Section A6.1

6. DECIDING TO TERMINATE TREATMENT USING REGRESSION ANALYSIS

The decision to stop treatment is based on many sources of information including (1) expert knowledge of the ground water system at the site; (2) mathematical modeling of how treatment affects ground water flows and contamination levels; and (3) statistical results from the monitoring wells from which levels of contamination can be modeled and extrapolated. This chapter is concerned with the third source of information. In particular, it describes how one statistical technique, known as regression analysis, can be used in conjunction with other sources of information to decide when to terminate treatment. The methods given here are applicable to analyzing data from the treatment period indicated by the unshaded portion of Figure 6.1. Methods other than regression analysis, such as time series analysis (Box and Jenkins, 1970) can also be used. However, these methods are usually computer intensive and require the assistance of a statistician familiar with these methods.

Figure 6.1 Example Scenario for Contaminant Measurements During Successful Remedial Action



Section 6.1 provides a brief overview of regression analysis and serves as a review of the basic concepts for those readers who have had some previous exposure to the subject. Section 6.2, the major focus of the chapter, provides a discussion of the steps required to implement a regression analysis of ground water remediation data. Section 6.3

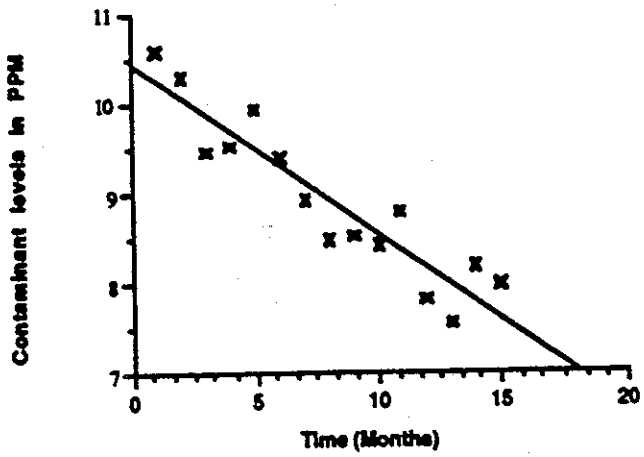
briefly outlines important considerations in combining statistical and nonstatistical information.

6.1 Introduction to Regression Analysis

Regression analysis is a statistical technique for fitting a theoretical curve to a set of sample data. For example, as a result of site clean-up, it is expected that contamination levels will decrease over time. Regression analysis provides a method for modeling (i.e., describing) the rate of this decrease. In ground-water monitoring studies, regression techniques can be used to (1) detect trends in contaminant concentration levels over time, (2) determine variables that influence concentration levels, and (3) predict chemical concentrations at future points in time. An example of a situation where a regression analysis might be useful is given in Figure 6.2 which shows a plot of chemical concentrations for 15 monthly samples taken from a hypothetical monitoring well during the period of treatment. As seen from the plot, there is a distinct downward trend in the observed chemical concentrations as a function of time. Moreover, aside from some "random" fluctuation, it appears that the functional relationship between contaminant levels and time can be reasonably approximated by a straight line for the time interval shown. This mathematical relationship is referred to as the regression "curve" or regression model. The goal of a regression analysis is to estimate the underlying functional relationship (i.e., the model), assess the fit of the model, and, if appropriate, use the model to make predictions about future observations.

In general, the underlying regression model need not be linear. However, to fix ideas, it is useful to introduce regression methods in the context of the **simple linear regression** model of which the linear relationship in Figure 6.2 is an example. Underlying assumptions, required notation, and the basic framework for simple linear regression analysis are provided in Section 6.1.1. Section 6.1.2 gives the formulas required to fit the regression model. Section 6.1.3 discusses how to evaluate the fit of the regression model using the residuals. Section 6.1.4 discusses how some important regression statistics can be used for inferential purposes (i.e., forming statistically defensible conclusions form the data).

Figure 6.2 Example of a Linear Relationship Between Chemical Concentration Measurements and Time



6.1.1 Definitions, Notation, and Assumptions

Assume that a total of N ground water samples have been taken from a monitoring well over a period of time for chemical measurement. Denote the sample collection time for i^{th} sample as t_i and the chemical concentration measurement in the i^{th} sample as c_i, where i = 1, 2, ..., N. Let y_i denote some function of the i^{th} observed concentration, for example, the identity function, $y_i = c_i$, the square root, $y_i = \sqrt{c_i}$, or the log transformation, $y_i = \ln(c_i)$. Let x_i denote time or a function of the time, for example, if the "time" variable is the original collection time, $x_i = t_i$, if the time variable is the reciprocal of the collection time then $x_i = 1/t_i$, etc. If the samples are collected at regular time intervals, then the time index, i, can be used to measure time in place of the actual collection time, i.e., $x_i = i$ or $x_i = 1/i$ in the examples above. Note that the notation used in this section is different from that introduced in Chapter 5.

The simple linear regression model relating the concentration measurements to time is defined by equation (6.1) in Box 6.1.

Box 6.1
Simple Linear Regression Model

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, \quad i = 1, 2, ..., N \qquad (6.1)$$

In equation (6.1), β_0 and β_1 are constants referred to as the **regression coefficients**, or alternatively as the **parameters of the model**, and ε_i is a random error. The term "y_i" is often referred to as the dependent, response, or outcome variable. In this document, the outcome variables of interest are contamination levels or related measures. The term "x_i" is also referred to as an independent or explanatory variable. The independent variable (for example the collection time) is generally under the control of the experimenter. The term N represents the number of observations or measurements on which the regression model is based.

The regression coefficients are unknown but can be estimated from the observed data under the assumption that the underlying model is correct. The non random part of the regression model is the formula for a straight line with **y-intercept** equal to β_0 and **slope** equal to β_1. In most regression applications, primary interest centers on the slope parameter. For example, if $x_i = i$ and the slope is negative, then the model states that the chemical concentrations decrease linearly with time, and the value of β_1 gives the rate at which the chemical concentrations decrease.

The random error, ε_i, represents "random" fluctuations of the observed chemical measurements around the hypothesized regression line, $y_i = \beta_0 + \beta_1 x_i$. It reflects the sources of variability not accounted for by the model, e.g., sources of variability due to unassignable or unmeasurable causes. Regression analysis imposes the following assumptions on the errors:

(i) The ε_i's are independent;

(ii) The ε_i's have mean 0 for all values of x_i;

(iii) The ε_i's have constant variance, σ^2, for all values of x_i; and

(iv) The ε_i's are normally distributed.

These assumptions are critical for the validity of the statistical tests used in a regression analysis. If they do not hold, steps must be taken to accommodate any departures from the underlying assumptions. Section 6.2.3 describes some simple graphical procedures which can be used to study the aptness of the underlying assumptions and also indicates some corrective measures when the above assumptions do not hold.

Interested readers should refer to Draper and Smith (1966) or Neter, Wasserman, and Kutner (1985) for more details on the theoretical aspects of regression analysis.

6.1.2 Computational Formulas for Simple Linear Regression

The computational formulas for most of the important quantities needed in a simple linear regression analysis are summarized below. These formulas are given primarily for completeness, but have been written in sufficient detail so that they can be used by persons wishing to carry out a simple regression analysis without the aid of a computer, spreadsheet, or scientific calculator. Readers who do not need to know the computational details in a regression analysis should skip this section and go directly to Sections 6.1.3 and 6.1.4, where specific procedures for assessing the fit of the model and making inferences based on regression model are discussed.

Estimates of the slope, β_1, and intercept, β_0, of the regression line are given by the values b_1 and b_0 in equations (6.2) and (6.3) in Box 6.2. The statistics b_1 and b_0 are referred to as **least squares estimates**. If the four critical assumptions given in Section 6.1.1 hold for the simple linear regression model in Box 6.1, b_1 and b_0 will be unbiased estimates of β_1 and β_0, and the precision of the estimates can be determined.

The estimated regression line (or, more generally, **the fitted curve**) under the model is represented by equation (6.4) in Box 6.3.

Box 6.2
Calculating Least Square Estimates

$$b_1 = \frac{\sum_{i=1}^{N} x_i y_i - \frac{\sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N}}{\sum_{i=1}^{N} x_i^2 - \frac{(\sum_{i=1}^{N} x_i)^2}{N}} = \frac{\sum_{i=1}^{N} x_i y_i - N\bar{x}\,\bar{y}}{\sum_{i=1}^{N} x_i^2 - N\bar{x}^2} \qquad (6.2)$$

$$b_0 = \frac{\sum_{i=1}^{N} y_i}{N} - b_1 \frac{\sum_{i=1}^{N} x_i}{N} = \bar{y} - b_1 \bar{x} \qquad (6.3)$$

Box 6.3
Estimated Regression Line

$$\hat{y}_i = b_0 + b_1 x_i \qquad (6.4)$$

The calculated value of $\hat{y}_i$ is called the **predicted value** under the model corresponding to the value of the independent variable, x_i. The difference between the predicted value, $\hat{y}_i$, and the observed value, y_i, is called the residual. The equation for calculating the residuals is shown in Box 6.4. If the model provides a good prediction of the data, we would expect the predicted values, $\hat{y}_i$, to be close to the observed values, y_i. Thus, the sum of the squared differences $(y_i - \hat{y}_i)^2$ provides a measure of how well the model fits the data and is a basic quantity necessary for assessing the model.

Box 6.4
Calculation of Residuals

$$e_i = y_i - \hat{y}_i \qquad (6.5)$$

Formally, we define the **sum of squares due to error (SSE)** and the corresponding **mean square error (MSE)** by formulas (6.5) and (6.6), respectively, in Box 6.5.

Box 6.5
Sum of Squares Due to Error and the Mean Square Error

$$SSE = \sum_{i=1}^{N} (y_i - \hat{y}_i)^2 \qquad (6.6)$$

$$MSE = \frac{SSE}{N-2}. \qquad (6.7)$$

As seen in the formulas in Box 6.2, the analysis of a simple linear regression model requires the computation of certain sums and sums of cross products of the observed data values. Therefore, it is convenient to define the five basic regression quantities in Box 6.6.

The estimated model parameters and SSE can be computed from these terms using the formulas in Box 6.7.

Box 6.6
Five Basic Quantities for Use in Simple Linear Regression Analysis

$$S_x = \sum_{i=1}^{N} x_i \tag{6.8}$$

$$S_y = \sum_{i=1}^{N} y_i \tag{6.9}$$

$$S_{xx} = \sum_{i=1}^{N} x_i^2 - \frac{S_x^2}{N} \tag{6.10}$$

$$S_{yy} = \sum_{i=1}^{N} y_i^2 - \frac{S_y^2}{N} \tag{6.11}$$

$$S_{yx} = \sum_{i=1}^{N} y_i x_i - \frac{S_y S_x}{N} \tag{6.12}$$

Box 6.7
Calculation of the Estimated Model Parameters and SSE

$$b_1 = \frac{S_{yx}}{S_{xx}} \tag{6.13}$$

$$b_0 = \frac{S_y}{N} - b_1 \frac{S_x}{N} \tag{6.14}$$

$$SSE = S_{yy} - \frac{S_{yx}^2}{S_{xx}} \tag{6.15}$$

An example of these basic regression calculations is presented in Box 6.8.

Box 6.8
Example of Basic Calculations for Linear Regression

Table 6.1 gives hypothetical water contamination levels for each of 15 consecutive months. A plot of the data is shown in Figure 6.3. Using the formulas in Box 6.5, the following quantities were calculated:

$S_x = 120$ $S_y = 137.4$ $S_{xx} = 280$ $S_{yy} = 11.801$
$S_{yx} = -51.05$ $\bar{y} = 9.16$ $\bar{x} = 8$

The estimated regression coefficients are then calculated as:
$\hat{b}_1 = -0.1823$ $\hat{b}_0 = 10.62$

Therefore the fitted model is

$$\hat{y}_i = \hat{b}_0 + \hat{b}_1 x_i = 10.62 - .1832 x_i$$

and, the corresponding mean square error is

$$MSE = SSE/(N - 2) = \frac{2.4935}{13} = .1918.$$

The straight line in Figure 6.4 is a plot of the fitted model.

Table 6.1 Hypothetical Data for the Regression Example in Figure 6.3

Time (Month)	Contamination (PPM)
1	10.6
2	10.4
3	9.5
4	9.6
5	10.0
6	9.5
7	8.9
8	9.5
9	9.6
10	9.4
11	8.75
12	7.8
13	7.6
14	8.25
15	8.0

Figure 6.3 Plot of data for from Table 6.1

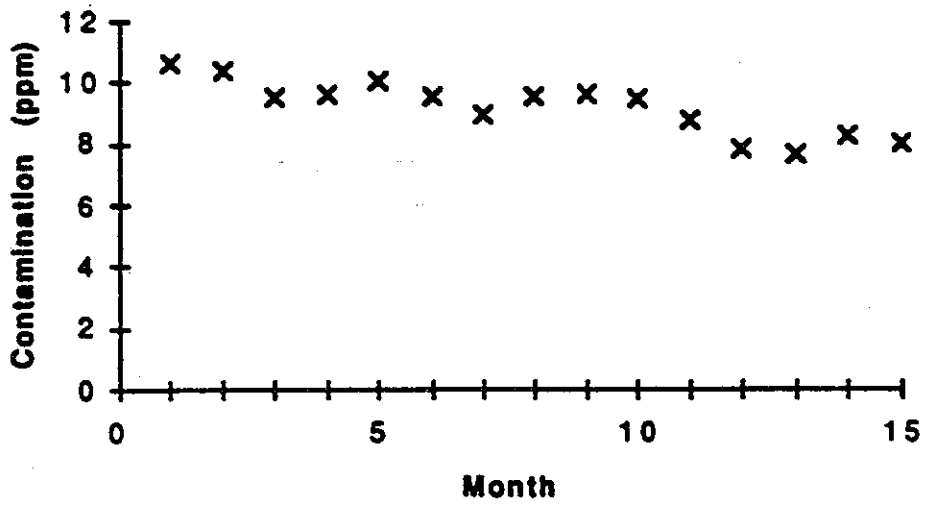
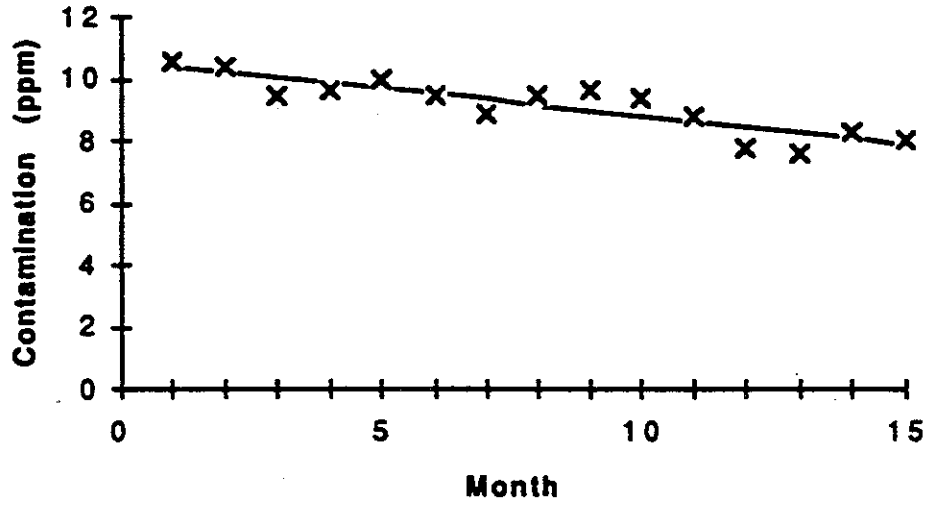


Figure 6.4 Plot of data and predicted values for from Table 6.1



6.1.3 Assessing the Fit of the Model

It is important to note that the computational procedures given in Section 6.1.2 can always be applied to a set of data, regardless of whether the assumed model is true. That is, it is always possible to fit a line (or curve) to a set of data. Whether the fitted model provides an adequate description of the observed pattern of data is a question that must be answered through examination of the "residuals." The residuals are the difference between the observed and predicted values for the dependent variable (see Box 6.4). If the model does not provide an adequate description of the data, examination of the residuals can provide clues on how to modify the model.

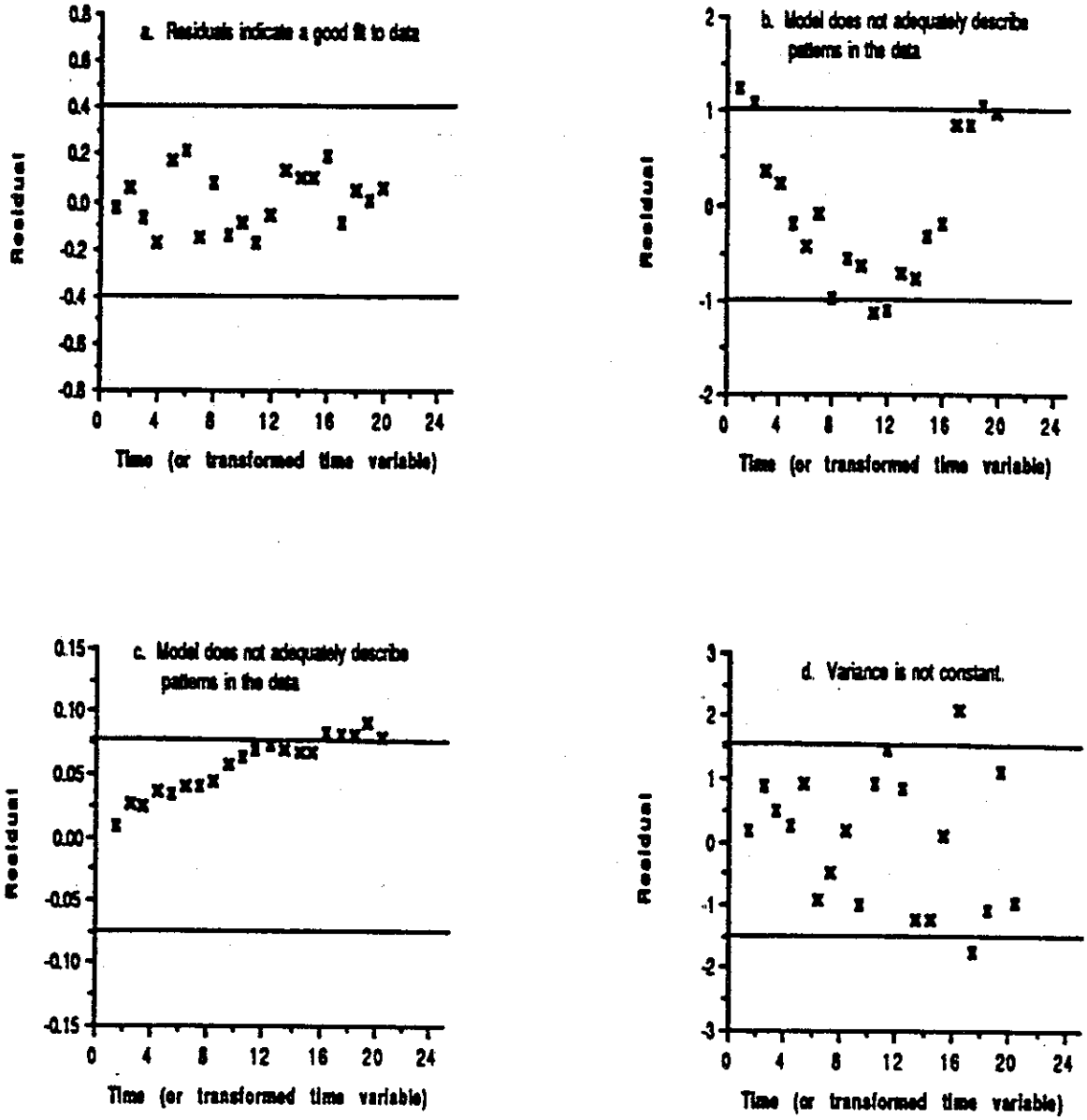
In a regression analysis, a **residual** is the difference between the observed concentration measurement, y_i and the corresponding fitted (predicted) value, $\hat{y}_i$ (Box 6.3). Recall that $\hat{y}_i = b_0 + b_1 x_i$, where b_0 and b_1 are the least squares estimates given by equations (6.3) and (6.2), respectively.

Since the residuals, e_i, estimate the underlying error, ε_i, the patterns exhibited by the residuals should be consistent with the assumptions given in Section 6.1.1 if the fitted model is correct. This means that the residuals should be randomly and approximately normally distributed around zero, independent, and have constant variance. Some graphical checks of these assumptions are indicated below. An example of an analysis of residuals is presented in Box 6.17.

1. To check for model fit, plot the residuals against the time index or the time variable, x_i. The appearance of cyclical or curvilinear patterns (see Figure 6.5, plots b and c) indicate lack of fit or inadequacy of the model (see Section 6.2.1 for a discussion of corrective measures).

2. To check for constancy of variance, examine the plot of the residuals against x_i and the plot of the residuals against the predicted value, $\hat{y}_i$. For both plots, the residuals should be confined within a horizontal band such as illustrated in Figure 6.5a. If the variability in the residuals increases such as in Figure 6.5d, the assumption of constant variance is violated (see Section 6.2.4 for a discussion of corrective measures in the presence of nonconstant variances).

Figure 6.5 Examples of Residual Plots (source: adapted from figures in Draper and Smith, 1966, page 89)

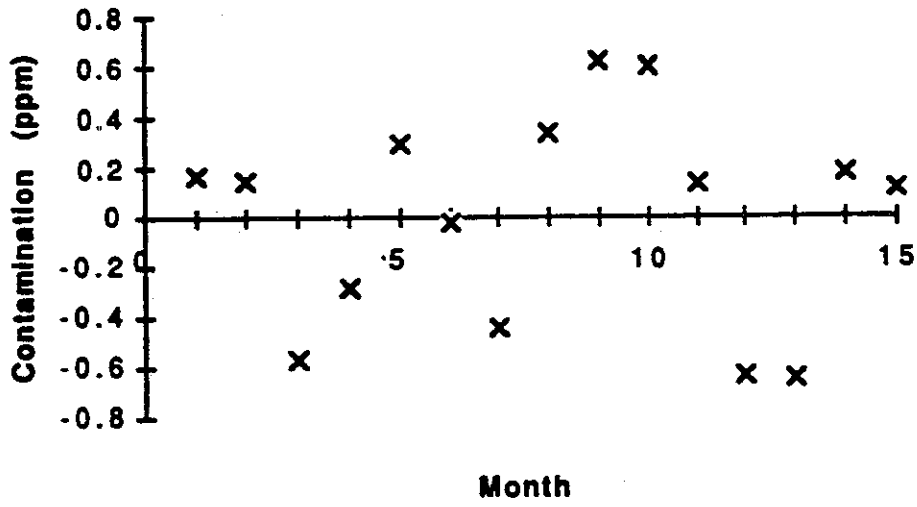


3. To check for normality of the residuals, plot the ordered residuals (from smallest to largest) against their expected values under normality, EV_i using the procedures of Section 5.7.2. Note that in this case, the formula for computing EV_i is given by equation (5.24) with s_{res} replaced by $\sqrt{MSE}$.

4. To test for independence of the error terms, compute the serial correlation of the residuals and perform the Durbin-Watson test (or the approximate large-sample test) described in Section 5.6.

It may happen that one or more of the underlying assumptions for linear regression is violated. Corrective measures are discussed in Section 6.2. Figure 6.6 shows the residuals for the analysis discussed in Box 6.8. These residuals can be compared to the examples in Figure 6.5.

Figure 6.6 Plot of residuals for from Table 6.1



6.1.4 Inferences in Regression

As mentioned earlier, two important goals of a regression analysis on ground water remediation are the determination of significant trends in the concentration measurements and the prediction of future concentration levels. Assuming that the hypothesized model is correct, the mean square error (MSE) defined by equation (6.6) plays an

important role in making inferences from regression models. The MSE is an estimate of that portion of the variance of the concentration measurements that is not explained by the model. It provides information about the precision of the estimated regression coefficients and predicted values, as well as the overall fit of the model.

6.1.4.1 Calculating the Coefficient of Determination

The **coefficient of determination**, denoted by R^2, is a descriptive statistic that provides a measure of the overall fit of the model and is defined in Box 6.9.

Box 6.9
Coefficient of Determination

$$R^2 = 1 - \frac{SSE}{S_{yy}}, \qquad (6.16)$$

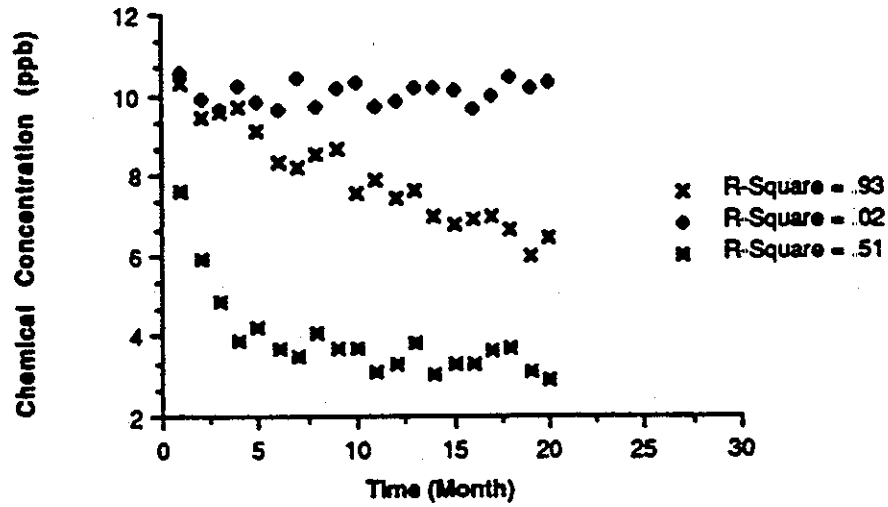
where SSE is given by equation (6.6) and S_{yy} is given by equation (6.11).

R^2 is always a number between 0 and 1 and can be interpreted as the proportion of the total variance in the y_i's that is accounted for by the regression model. If R^2 is close to 1 then the regression model provides a much better prediction of individual observations than does the mean of the observations. If R^2 is close to 0 then using the regression equation to predict future observations is not much better than using the mean of the y_i's to predict future observations. A perfect fit (i.e., when all of the observed data points fall on the fitted regression line) would be indicated by an R^2 equal to 1. In practice, a value of R^2 of 0.6 or greater is usually considered to be high and thus an indicator that the model can be reasonably used for predicting future observations; however, it is not a guarantee. A plot of the predicted values from the model and the corresponding observed values should be examined to assess the usefulness of the model.

Figure 6.7 shows the R^2 values for several hypothetical data sets. Notice that the data in the middle of the chart (represented by the symbol "x") exhibit a pronounced

downward linear trend, and this is reflected in a high R^2 of .93. On the other hand, the set of data in the top of the chart (represented by "diamonds") exhibits no trend in concentrations, and this is reflected in a low R^2 of .02. Finally, we note that the R^2 for the set of data at the bottom of the chart is fairly low (about 0.5), even though there appears to be a fairly strong (nonlinear) trend. This is because R^2 measures the linear trend over time (months). For these data, the trend in the concentrations is not linear; thus the corresponding R^2 is fairly low. If the time axis were transformed to the reciprocal of time, the resulting R^2 for the third data set would be close to 0.90.

Figure 6.7 Examples of R-Square for Selected Data Sets



While R^2 is a useful indicator of the fit of a model and the usefulness of the model for predicting individual observations, it is not definitive. If the model is used to predict the mean concentration rather than an individual observation or if the trend in the concentrations is of interest, other measures of the model fit are more useful. These are addressed in the following sections.

6.1.4.2 Calculating the Standard Error of the Estimated Slope

In a simple linear regression, the slope of the fitted regression line gives the magnitude and direction of the underlying trend (if any). Because different sets of samples would provide different estimates of the slope, the estimated slope given by equation (6.2) is subject to sampling variability. Even if the form of the assumed model (6.1) were known to be true, it would still not be possible to determine the slope of the true relationship exactly. However, it is possible to estimate, with a specified degree of confidence, a range within which the true slope is expected to fall.

The **standard error of b_1** provides a measure of the variability of the estimated slope. It is denoted by $s(b_1)$ and is defined in Box 6.10.

Box 6.10
Calculating the Standard Error of the Estimated Slope

$$s(b_1) = \sqrt{\frac{MSE}{S_{xx}}} \qquad (6.17)$$

The standard error can be used to construct a confidence interval around the true slope of the regression line. The formula for a $100(1-\alpha)$ percent confidence interval is given by equation (6.17) in Box 6.11.

Box 6.11
Calculating a Confidence Interval Around the Slope

$$b_1 \pm t_{1-\alpha/2;N-2}\, s(b_1) \qquad (6.18)$$

where $t_{1-\alpha/2;N-2}$ is the upper $1-\frac{\alpha}{2}$ percentage point of a t distribution with N-2 degrees of freedom (see Appendix Table A.1).

The confidence interval provides a measure of reliability for the estimated value b_1. The narrower the interval, the greater is the precision of the estimate b_1. Because the confidence interval provides a range of likely values of β_1 when the model holds, it can be used to test hypotheses concerning the significance of the observed trend.

6.1.4.3 Decision Rule for Identifying Significant Trends

If the confidence interval given by equation (6.17) contains the value zero, there is insufficient evidence (at the α significance level) to conclude that there is a trend.

On the other hand, if the confidence interval includes only negative (or only positive) values, we would conclude that there is a significant negative (or positive) trend.

An example in which the above decision rule is used to identify a significant trend is given in Box 6.12.

6.1.4.4 Predicting Future Observations

If the fitted model is appropriate, then an unbiased prediction of the concentration level at time h is $\hat{y}_h = b_0 + b_1 x_h$, where x_h is the value of the time variable at time h. The standard error of the estimate is given by equation (6.18), and the corresponding 100(1 - α) percent confidence limits around the predicted value at time h are given by formula (6.19) in Box 6.13.

Note that if the fitted regression model is based on data collected during the cleanup period, the confidence limits given by formula (6.20) may not strictly apply after treatment is terminated. Consequently, confidence limits based on data from the treatment period which are used to draw inferences about the post-treatment period should be interpreted with caution. Further discussion of the use of predicted values in ground water monitoring studies is given in Section 6.2.

Box 6.12
Using the Confidence Interval for the Slope to Identify a Significant Trend

For the data in Table 6.1, the estimated regression line was determined to be $\hat{y}_i = \hat{b}_0 + \hat{b}_1 x_i = 10.62 - .1823\, x_i$.

The coefficient of determination for the fitted model is $R^2 = 1 - \frac{SSE}{S_{yy}}$ = 1 - (2.49/11.8) = .79. That is, 79 percent of the variability in the contamination measurements is explained by the regression model provided that the model is correct.

Using equation (6.16), the standard error of the estimated slope is $s(b_1) = \sqrt{\frac{MSE}{S_{xx}}} = \sqrt{\frac{.191807}{240}} = .02617$; and the corresponding 95 percent confidence limits for β_1 are given by $-.1823 \pm (2.101)(.02617)$ or -.2373 to -.1273. (Note that $\alpha = .05$, $1 - \frac{\alpha}{2} = .975$, N = 15, and N-2 = 13; thus, $t_{1-\alpha/2,N-2} = t_{.925,13} = 2.101$ from Appendix Table A.1.)

Since the interval (-.2373, -.1273) does not include zero, we can conclude that the observed downward trend is significant at the $\alpha = .05$ level. That is, we have high confidence that the observed downward trend is real and not just due to sample variability.

Box 6.13
Calculating the Standard Error and Confidence Intervals for Predicted Values

$$s(\hat{y}_h) = \sqrt{MSE\ \{1 + \frac{1}{N} + \frac{(x_h - \bar{x})^2}{S_{xx}}\}} \qquad (6.19)$$

$$\hat{y}_h \pm t_{1-\alpha/2;N-2}\, s(\hat{y}_h) \qquad (6.20)$$

An example in which the regression model is used to predict future values is presented in Box 6.14.

Box 6.14
Using the Simple Regression Model to Predict Future Values

Continuing the example in Box 6.11, suppose that the site manager is interested in predicting the contaminant concentration for month 16*. The predicted concentration level for month 16, assuming that the model holds, is

$$\hat{y}_{16} = b_0 + b_1 x_{16} = 10.62 - .1823(16) = 7.703.$$

The standard error of the predicted value is

$$s(\hat{y}_{16}) = \sqrt{MSE \left\{1 + \frac{1}{N} + \frac{(x_{16} - \bar{x})^2}{S_{xx}}\right\}}$$

$$= \sqrt{.1918 \left(1 + \frac{1}{15} + \frac{(16 - 8)^2}{280}\right)} = .4984.$$

Therefore, if the model holds, 99 percent confidence limits around the predicted value [see formula (6.20)] are given by 7.703 ± 2.878 (.4984) or from 6.269 to 9.137.

* Again, it should be emphasized that whenever a regression model is used to make predictions about concentrations outside the range of the sampling period, extreme caution should be used in interpreting the results. In particular, the regression results should not be used alone, but should be combined with other sources of information (see discussion in Section 6.3).

6.1.4.5 Predicting Future Mean Concentrations

If the fitted model is appropriate, then an unbiased prediction of the mean concentration level at time h is $\hat{y}_h = b_0 + b_1 x_h$, where x_h is the value of the time variable at time h. Although the predicted mean and the predicted value for an individual observation are the same, the prediction error of the predicted mean is less than that for an individual predicted value. The standard error of the predicted mean is given by equation (6.21), and the corresponding $100(1 - \alpha)$ percent confidence limits around the predicted mean at time h are given by formula (6.22) in Box 6.15.

Box 6.15
Calculating the Standard Error and Confidence Interval a Predicted Mean

$$s(\hat{y}_h) = \sqrt{MSE \left\{\frac{1}{N} + \frac{(x_h - \bar{x})^2}{S_{xx}}\right\}} \qquad (6.21)$$

$$\hat{y}_h \pm t_{1-\alpha/2;N-2}\, s(\hat{y}_h) \qquad (6.22)$$

Note that if the fitted regression model is based on data collected during the cleanup period, the confidence limits given by formula (6.19) may not strictly apply after treatment is terminated. Consequently, confidence limits based on data from the treatment period which are used to draw inferences about the post-treatment period should be interpreted with caution. Further discussion of the use of predicted values in ground water monitoring studies is given in Section 6.2.

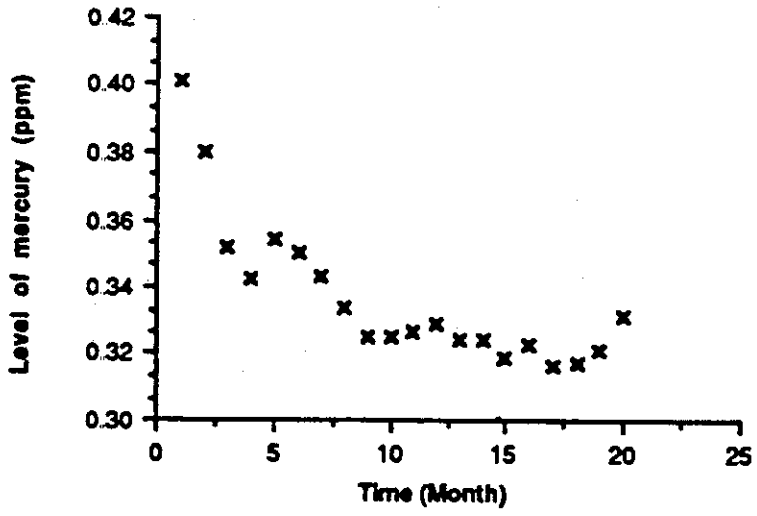
6.1.4.6 Example of a "Nonlinear" Regression

Applying regression analysis is not always as straightforward as the examples in Boxes 6.8, and 6.12 indicate. To show some of the possible complexities and to help fix some of the ideas presented, we will do a regression analysis on the data in Table 6.2. As shown in Figure 6.8, these data are not linear with respect to time and hence a transformation of the independent variable was employed. (More information about the use of transformations is given later in Section 6.2.3.) The analysis is summarized in Box 6.16 and the fitted model is plotted in Figure 6.9.

Table 6.2 Hypothetical concentration measurement for mercury (Hg) in ppm for 20 ground water samples taken at monthly intervals

Month	Year	Coded month (i)	Concentration (y)	Reciprocal of month (x)
January	1986	1	0.401	1.0000
February	1986	2	0.380	0.5000
March	1986	3	0.352	0.3333
April	1986	4	0.343	0.2500
May	1986	5	0.354	0.2000
June	1986	6	0.350	0.1667
July	1986	7	0.343	0.1429
August	1986	8	0.333	0.1250
September	1986	9	0.325	0.1111
October	1986	10	0.325	0.1000
November	1986	11	0.327	0.0909
December	1986	12	0.329	0.0833
January	1987	13	0.324	0.0769
February	1987	14	0.325	0.0714
March	1987	15	0.319	0.0667
April	1987	16	0.323	0.0625
May	1987	17	0.316	0.0588
June	1987	18	0.318	0.0556
July	1987	19	0.321	0.0526
August	1987	20	0.331	0.0500

Figure 6.8 Plot of Mercury Measurements as a Function of Time (See Box 6.16)



Box 6.16
Example of Basic Regression Calculations

Table 6.2 shows mercury concentrations for 20 ground water samples taken from January 1986 to August 1987. A plot of the concentration measurements as a function of time is shown in Figure 6.8. Because the data exhibited a nonlinear trend, it was decided to consider the model $y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$, where $x_i = 1/i$. The values of the reciprocals of time are shown in the last column of the table.

For these data, the following quantities were calculated: $S_x = 3.598$; $S_y = 6.739$; $S_{xx} = .949$; $S_{yy} = .00909$; $S_{yx} = .0866$, $y = .337$, $\bar{y} = .337$, $\bar{x} = .180$.

The estimated regression coefficients were then calculated as: $b_1 = .0866/.949 = .0913$; and $b_0 = .337 - (.0913)(.180) = .321$. The fitted model is therefore

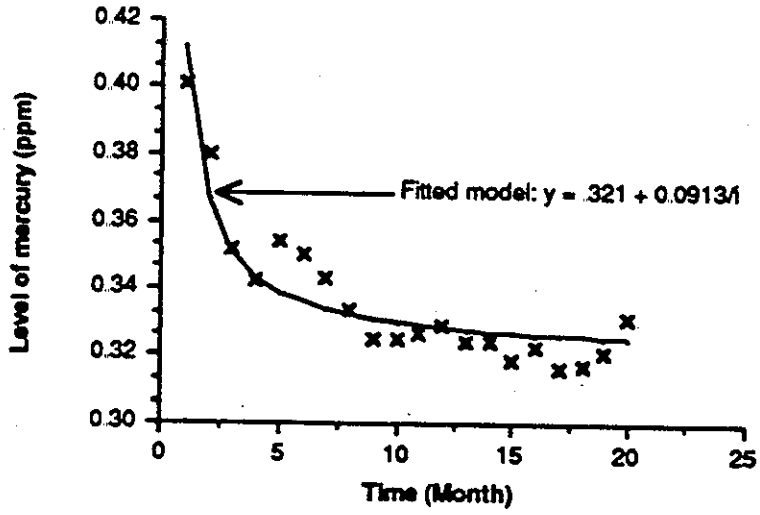
$$\hat{y}_i = b_0 + b_1 x_1 = .321 + \frac{.0913}{i}$$

and the associated mean square error is

$$MSE = \frac{SSE}{18} = \frac{.00909 - \frac{.0866^2}{.949}}{18} = .000066.$$

Figure 6.9 shows a plot of the fitted model against the observed concentration values.

Figure 6.9 Comparison of Observed Mercury Measurements and Predicted Values under the Fitted Model (See Box 6.16)



Box 6.17
Analysis of Residuals for Mercury Example

Figure 6.10 shows a plot of the residuals for the mercury data in Table 6.2 based on the fitted model, $\hat{y}_i = .321 + 0.0913/i$ (see Box 6.16). The residual plot indicates some lack of fit of the model. In particular, it appears that the fitted model tends to underestimate concentrations at the earlier times while overestimating concentrations at the later times. (Since the residuals represent the differences between the actual and predicted values, the positive values of the residuals in the earlier months indicate that the actual values tend to be larger than the predicted values then. Hence, the model underestimates the earlier concentrations.)

To see whether the fit could be improved by using a different transformation of i, the following alternative model was considered: $y_i = \beta_0 + \beta_1/\sqrt{i} + \varepsilon_i$. For this model, the estimated regression coefficients are $b_0 = .2957$ and $b_1 = .1087$, and the coefficient of determination is $R^2 = .927$ (compared to .89 for the earlier model). This indicates a somewhat better fit when $1/\sqrt{i}$ is used as the independent variable (see Figure 6.11). The residual plot under the new model (see Figure 6.12) seems to support this conclusion. Moreover, the standard error of b_1 is $s(b_1) = .0072$, and hence 95 percent confidence limits around the true slope are given by $.1087 \pm (2.101)(.0072)$, or .094 to .124. Since the interval does not include zero, we further conclude that the trend is significant.

Finally, Figure 6.13 shows a normal probability plot of the ordered residuals based on the revised model, where the expected values, EV_i were computed using formula (5.24) with $s_{res} = \sqrt{MSE}$. There is a nonlinear pattern in the residuals which suggests that the normality assumption may not be appropriate for this model. If a formal test indicates the lack of normality is significant, nonlinear regression procedures should be considered.

Figure 6.10 Plot of Residuals Against Time for Mercury Example (see Box 6.17)

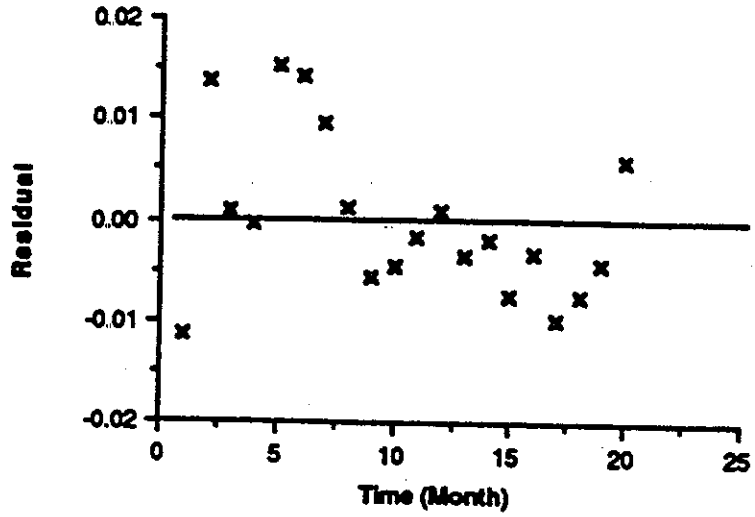


Figure 6.11 Plot of Mercury Concentrations Against $x = 1/\sqrt{i}$, and Alternative Fitted Model (see Box 6.17)

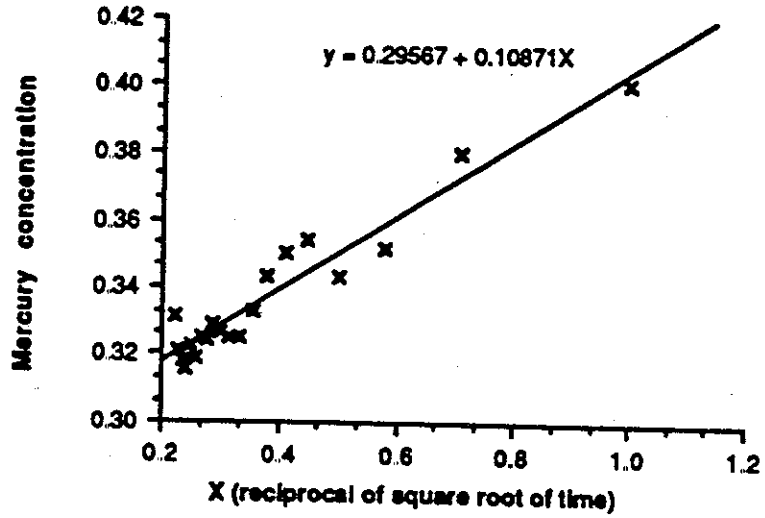


Figure 6.12 Plot of Residuals Based on Alternative Model (see Box 6.17)

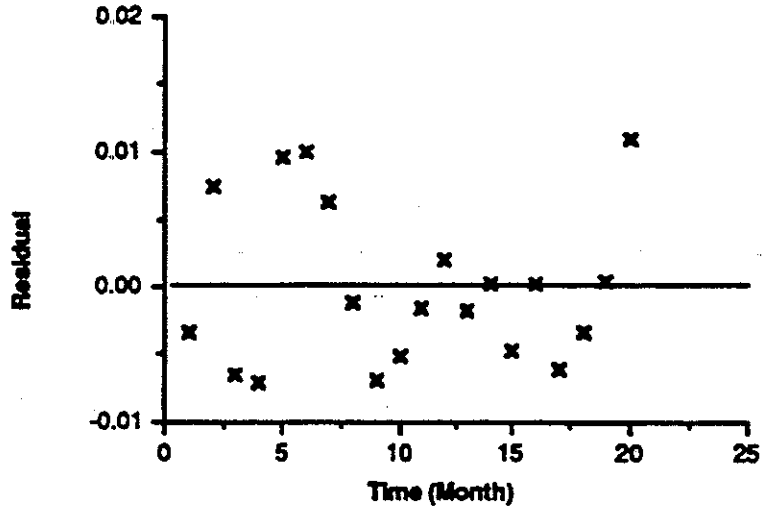
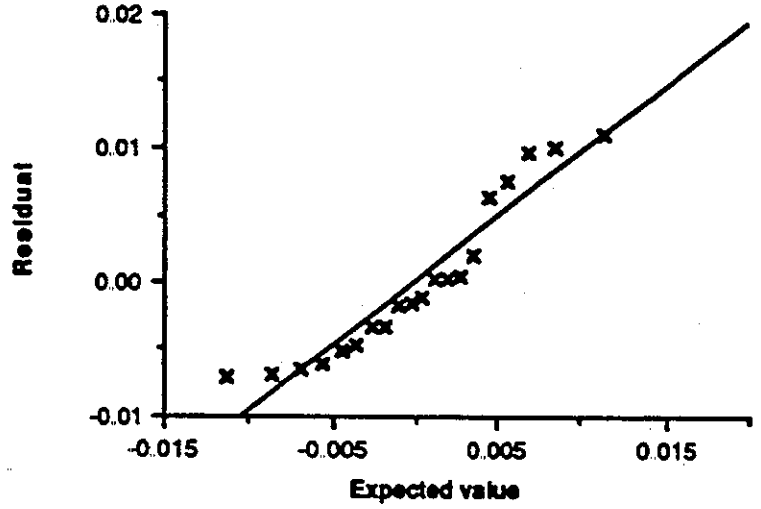


Figure 6.13 Plot of Ordered Residuals Versus Expected Values for Alternative Model (see Box 6.17)



To summarize, if the data are originally linear (such as the data in Table 6.1), then we may fit the simple linear regression model of Box 6.1. If the data are more complex (e.g. the data in Table 6.2), then a transformation may be used as was done in Box 6.16. One can transform either the independent (i.e., the explanatory) variable or the dependent (i.e., the outcome) variable, or both. Finding the appropriate transformation is as much an art as it is a science. Consultation with a statistician is recommended in order to help identify useful transformations and to help interpret the model based on the transformed data.

6.2 Using Regression to Model the Progress of Ground Water Remediation

As samples are collected and analyzed during the cleanup period, trends or other patterns in the concentration levels may become evident. As illustrated in Figure 6.14, a variety of patterns are possible. In situation 1, regression might be used to determine the slope for observations beyond time 20 to infer if the treatment is effective. If not, a decision might be made to consider a different remedial program. For Situation 2, the concentration measurements have decreased below the cleanup standard, and regression might be used to investigate whether the concentrations can be expected to stay below the cleanup standard. For Situation 3 in Figure 6.14, which could arise from factors such as interruptions or changes in the treatment technology or fluctuating environmental conditions, regression can be used to assess trends. However, due to the highly erratic nature of the data any predictions of trends of future concentrations are likely to be very inaccurate. Additional data collection will be necessary before conclusions can be reached. Where appropriate, regression analysis can be useful in estimating and assessing the significance of observed trends and in predicting expected levels of contaminant concentrations at future points in time.

Figure 6.15 summarizes the steps for implementing a simple linear regression analysis at Superfund sites. These steps are described in detail in the sections that follow.

Figure 6.14 Examples of Contaminant Concentrations that Could Be Observed During Cleanup

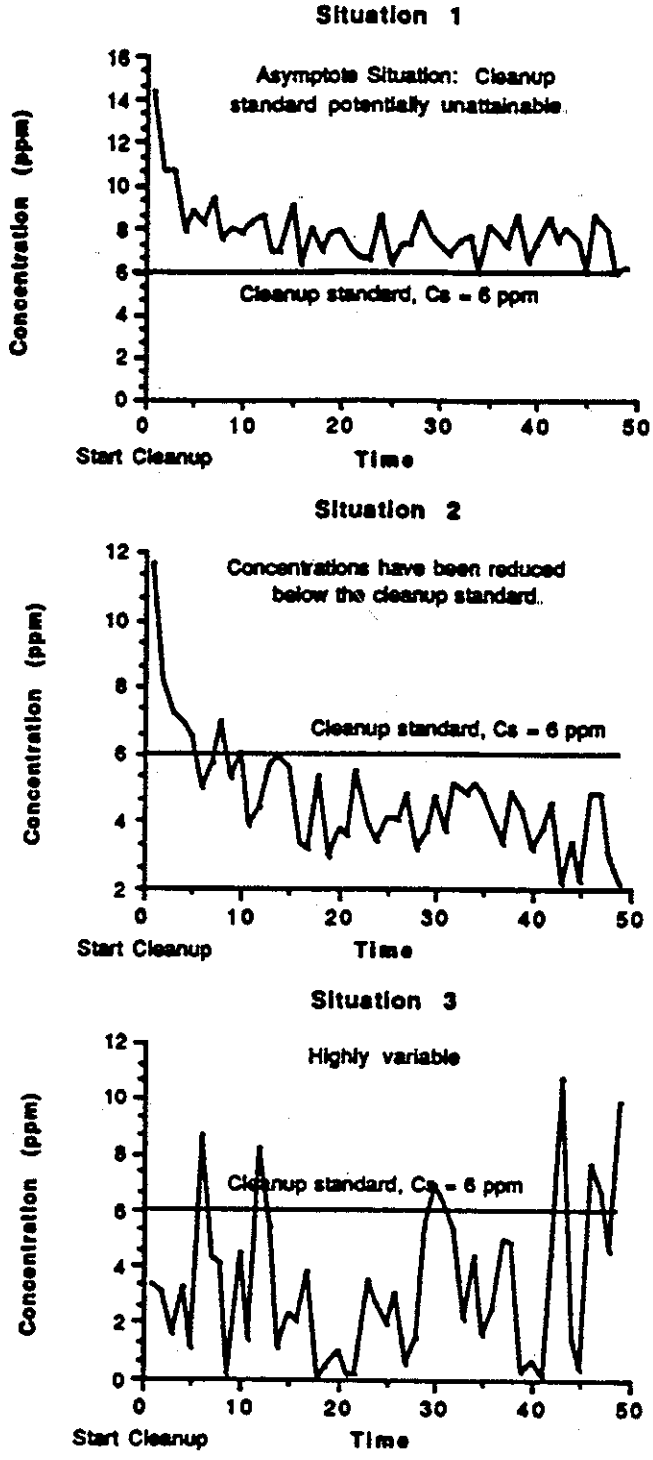
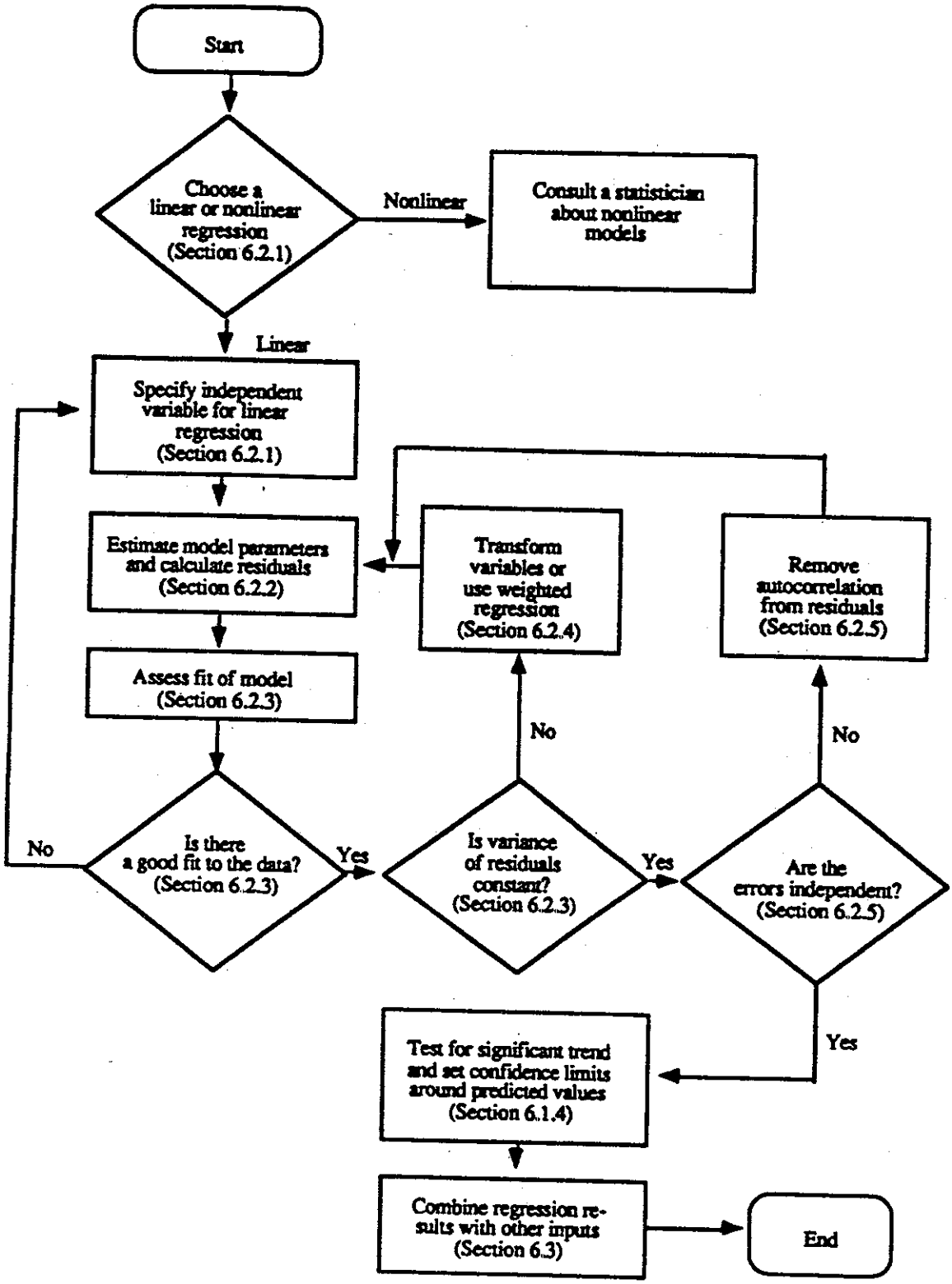


Figure 6.15 Steps for Implementing Regression Analysis at Superfund Sites



6.2.1 Choosing a Linear or Nonlinear Regression

The first step in a regression analysis is to decide whether a linear or nonlinear model is appropriate. An initial choice can often be made by observing a plot of the sample data over time. For example, for the data of Figure 6.2, the relationship between concentration measurements and time is apparently linear. In this case, the regression model (6.1) with $x_i = i$ would be appropriate. However, for the data displayed in Figure 6.16, some sort of nonlinear model would be appropriate.

Sometimes it is possible to model a nonlinear relationship such as that shown in Figure 6.16 with linear regression techniques by transforming either the dependent or independent variable.[1] In some cases, theoretical considerations of ground water flows and the type of treatment applied may lead to the formulation of a particular nonlinear model such as "exponential decay." This, in turn, may lead to consideration of a particular type of transformation (e.g., logarithmic or inverse transformations). However, these a priori considerations do not preclude testing the model for adequacy of fit. Choosing the appropriate transformation may require the assistance of a statistician; however, if the (nonlinear) relationship is not too complicated, some relatively simple transformations may be sufficient to "linearize" the model, and the procedures given in Section 6.1 may be used. On the other hand, after analysis of the residuals (as described below in Section 6.2.3), if none of the given transformations appears to be adequate, nonlinear regression methods should be used (see Draper and Smith, 1966; Neter, Wasserman, and Kutner, 1985). A statistician should be consulted about these methods.

Figure 6.17 shows examples of two general types of curves that might reasonably approximate the relationship between observed contaminant levels and time. If a plot of the concentration measurements versus time exhibits one of these patterns, the transformations listed below in Box 6.18 may be helpful in making the model linear. Since the initial choice of transformation may not provide a "good" fit, the process of determining the appropriate transformation may require several iterations. The procedures described in Section 6.2.3 can be used to assess the fit of a particular model. Box 6.18 contains some suggested transformations for the two types of curves shown in Figure 6.17 (source: Neter, Wasserman, and Kutner, 1985).

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[1] Although a model such as $y = \beta_0 + \beta_1 \left(\frac{1}{x}\right)$ is a nonlinear equation; it is called a linear regression model because the coefficients, β_0 and β_1, occur in a linear form (as opposed to say $y = \beta_0 + x^{\beta_1}$).

Figure 6.16 Example of a Nonlinear Relationship Between Chemical Concentration Measurements and Time

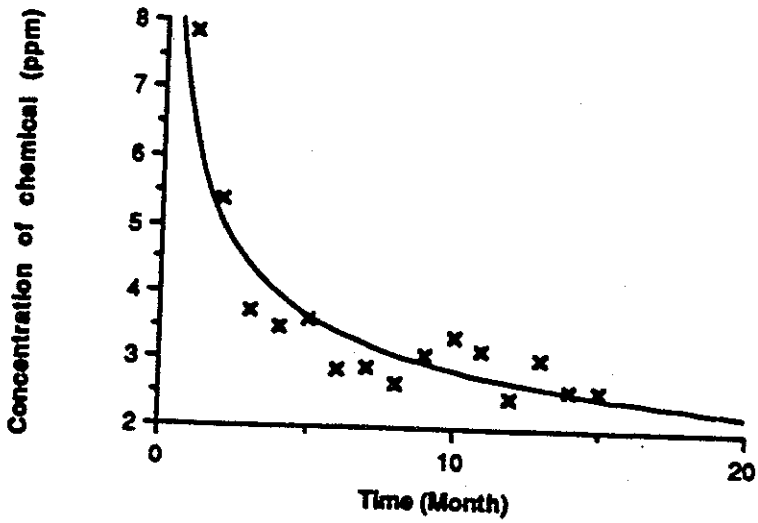
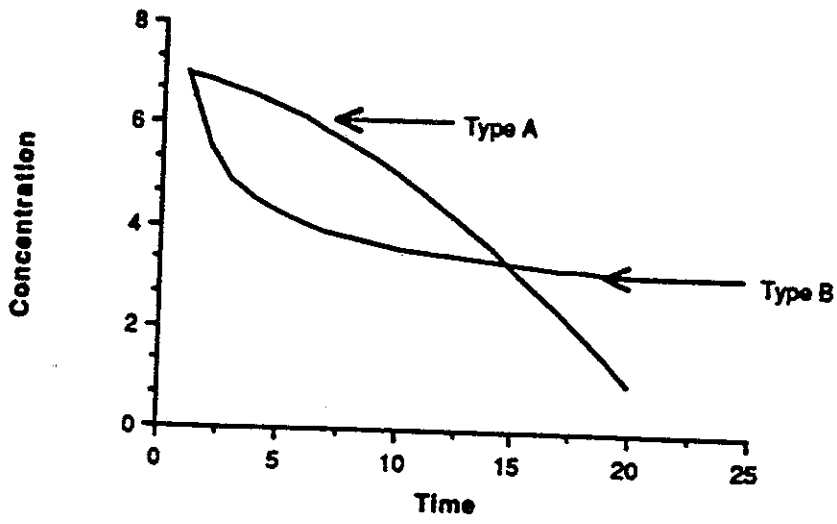


Figure 6.17 Examples of Nonlinear Relationships



Box 6.18
Suggested Transformations

Type A: Contaminant concentrations following this pattern decrease slowly at first and then more rapidly later on. A useful transformation to consider is

$$x_i = i^p$$

where p is a constant greater than 1. If the decline in concentrations is very steep, set $p = 2$, initially, and then try alternative values, if necessary, to obtain a good fit.

Type B: Contaminant concentrations following this pattern decrease rapidly at first and then more slowly later on. Useful transformations to consider in this case are

- $x_i = \frac{1}{i}$
- $x_i = 1/\sqrt{i}$
- $x_i = \log(i)$
- $x_i = \sqrt{i}.$

Alternatively, one can also consider transforming y_i; e.g., use the transformed variable

- $y_i' = \sqrt{y_i}$
- $y_i' = \log(y_i)$
- $y_i' = 1/y_i$

either in lieu of or together with the transformed time variable, whichever appears to be appropriate.

There is no guarantee that using transformations will help; and its effectiveness must be determined by checking the fit of the model and examining the residuals. Consultation with a statistician is recommended to help identify useful transformations and to interpret the model based on the transformed measurements.

6.2.2 Fitting the Model

In a regression analysis, the process of "fitting the model" refers to the process of estimating the regression parameters and associated sampling errors from the observed data. With these estimates, it is then possible to (1) determine whether the model provides an adequate description of the observed chemical measurements; (2) test whether there is a significant trend in the chemical measurements over time; and (3) obtain estimates of concentration levels at future points in time.

Given a set of concentration measurements, y_i, $i = 1, 2, ..., N$, and corresponding time values, x_i, the estimated slope and intercept of the fitted regression line can be computed from the equations in Section 6.1.2. For the fitted model, the error sum of squares, SSE, and coefficient of determination should also be computed.

Note that the model fitting will, in general, be an iterative process. If the fitted model is inadequate for any of the reasons indicated below in Section 6.2.3, it may be possible to obtain a better fitting model by considering transformations of the data.

6.2.3 Regression in the Presence of Nonconstant Variances

If the residuals for a fitted model exhibit a pattern such as that shown in Figure 6.14d, the assumption of constant variance is violated, and corrective steps must be taken. The two most common corrective measures are: (1) transform the dependent variable to stabilize the variance; or (2) perform a "weighted least squares regression" (Neter, Wasserman, and Kutner, 1985).

Transformations of the dependent variable that are useful for stabilizing variances are the square root transformation, the logarithmic transformation, and the inverse transformation. Which transformation to use in a particular situation depends on the way the variance increases. To determine this relationship, it is useful to divide the data into four or five groups based on the time at which observations were made. For example, the first group might consist of the first four observations, the second group might consist of the next four observations, and so on. For the g^{th} group, compute the mean of the observed concentrations, $\bar{y}_g$, and the standard deviation of the concentrations, s_g (Section 5.1). If a plot of s_g^2 versus $\bar{y}_g$ is approximately a straight line, use $\sqrt{y_i}$, the square root

transformation, in the regression analysis; if a plot of s_g versus $\bar{y}_g$ is approximately a straight line, use $\log(y_i)$, the logarithmic transformation, in the analysis; and, finally, if a plot of $\sqrt{s_g}$ versus $\bar{y}_g$ is approximately a straight line, use $\frac{1}{y_i}$, the inverse transformation, in the analysis (Neter, Wasserman, and Kutner, 1985).

The other major method for dealing with nonconstant variance is **weighted least squares** regression. Weighted least squares analysis provides a formal way of accommodating nonconstant variance in regression. To apply this method, the form of the underlying variance structure must be known or estimated from the data. This method is described elsewhere; e.g., Draper and Smith (1966). A statistician should be consulted when applying these methods.

6.2.4 Correcting for Serial Correlation

It is sometimes possible to remove the serial correlation in the residuals by transforming the dependent and independent variables. Applied Linear Statistical Models by Neter, Wasserman, and Kutner (1985), amplifies the following iterative procedure.

6.2.4.1 Fitting the Model

The four steps for fitting the model to remove serial correlations are discussed below.

(1) Calculate the serial correlation of the residuals, $\hat{\phi}_{obs}$, using the formula in Box 5.14.

(2) For i = 2, 3, ..., N, transform both the dependent and independent variables using equation (6.23) in Box 6.19. Perform an ordinary least squares regression on the transformed variables. That is, using the procedures of Section 6.1.2, fit the "new" model given by equation (6.24).

Box 6.19
Transformation to "New" Model

Transform both the dependent and independent variables using the formulas:

$$y_i' = y_i - \hat{\phi}_{obs} y_{i-1} \quad \text{and} \quad x_i' = x_i - \hat{\phi}_{obs} x_{i-1}, \tag{6.23}$$

Fit the following model using the transformed variables:

$$y_i' = \beta_0' + \beta_1' x_i' + e_i . \tag{6.24}$$

Note that one observation is lost in the transformed measurements because (6.26) cannot be determined for i = 1.

Denote the least squares estimates of the parameters of the new (transformed) model by b_0' and b_1' and denote the fitted model for the transformed variables by equation (6.25) in Box 6.20.

Box 6.20
"New" Fitted Model for Transformed Variables

$$\hat{y}_i' = b_0' + b_1' x_i' \tag{6.25}$$

Calculate the residuals for the new model: $e_i' = y_i' - (b_0' + b_1' x_i')$. Note that the fitted model (6.25) is expressed in terms of the transformed variables and not the original variables.

(3) Perform the Durbin-Watson test (or approximate test if the sample size is large) on the residuals of the model fitted in step (2). If the test indicates that the serial correlation is not significant, go to step (4). Otherwise, terminate the process and consult a statistician for alternative methods of correcting for serial correlation.

(4) In terms of the original variables, the slope and the intercept of the fitted regression line are provided in Box 6.21.

Box 6.21
Slope and Intercept of Fitted Regression Line in Terms of Original Variables

$$b_1 = b_1' \text{ and } b_0 = \frac{b_0'}{1 - \hat{\phi}_{obs}} \qquad (6.26)$$

where $\hat{\phi}_{obs}$ is the estimated autocorrelation determined by using the residuals obtained from fitting the untransformed data, and b_0' and b_1' are least squares estimates obtained from the transformed data.

The approach given above has the effect of adjusting the estimates of variance to account for the presence of autocorrelation. Typically, the variance of the estimated regression coefficients is larger when the errors are correlated, as compared with uncorrelated errors. An example of the use of this technique is given in Box 6.22.

6.2.4.2 Determining Whether the Slope is Significant

The standard error of the slope of the original model is simply the standard error of the slope, b_1', obtained from the regression analysis performed on the transformed data defined in Box 6.21. The formulas given in Section 6.1.4 can be used to compute the standard error of b_1'. The decision rule in Section 6.1.4.3 can be used to identify whether the trend is statistically significant. Note that for the transformed data, the total number of observations is N-1.

Box 6.22
Correcting for Serial Correlation

Table 6.3 shows the concentration of benzene in 15 quarterly ground water samples taken from a monitoring well at a former manufacturing site. It appeared from a plot of the data (see Figure 6.18) that a simple linear model of the form: $y_i = \beta_0 + \beta_1 i + \varepsilon_i$ might be appropriate in describing the relationship between concentrations and time.

A regression analysis was performed on the data with the following results: (a) the fitted model was estimated to be $\hat{y}_i = 29.20 - .478i$; (b) $R^2 = 0.73$; (c) 95 percent confidence limits around the slope of the line were calculated to be $-0.478 \pm (2.16)(.082)$, or -0.66 to -0.30; and (d) the Durbin-Watson statistic was computed to be D = .795.

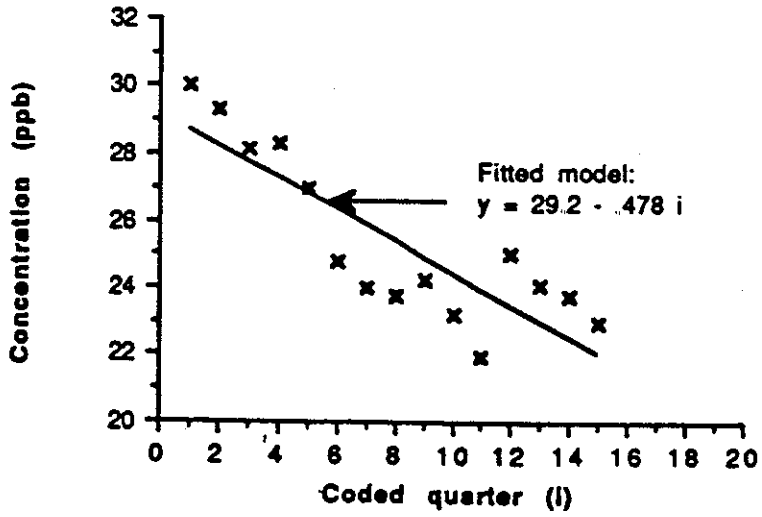
For N = 15 and p-1=1 (there are two parameters in the model), the critical value for the Durbin-Watson test is $d_U = 1.36$ at the .05 significance level. Since D < 1.36, it was concluded that there was a significant autocorrelation. Although the calculated confidence interval for the slope of the line apparently indicated that the observed downward trend was significant, it was recognized that the presence of autocorrelations could lead to erroneous conclusions. Therefore, the data were re-analyzed using the method of transformations described earlier in this section.

First, the serial correlation was computed from the residuals as $\hat{\phi}_{obs} = .57$. Then the observed concentrations and time variable were transformed as follows: $y_i' = y_i - .57y_{i-1}$; and $x_i' = i - .57(i-1)$. A regression of y_i' on x_i' resulted in least squares estimates of $b_1' = -.34$ and $b_0' = 11.89$ for the transformed variables, with $s(b_1') = .17$. Therefore, using equation (6.26), estimates of the slope and intercept for the original data were calculated as $b_1 = b_1' = -.34$, and $b_0 = \frac{b_0'}{1-.57} = \frac{11.89}{.43} = 27.65$. Note that the revised estimates are close to the original estimates, except that now the standard error of b_1 is much larger that it was before the effect of the autocorrelations was taken into account in the analysis (.17 vs. .082). Because of this increase in variance, 95 percent confidence limits around the true slope are now given by $-.34 \pm (2.179)(.17)$, or -.71 to .03. In this case, the interval includes zero, and therefore at the five percent significance level, we cannot conclude that the observed trend is significant.

Table 6.3 Benzene concentrations in 15 quarterly samples (see Box 6.22)

Year	Quarter	Coded quarter (i)	Concentration in ppb (y)
1985	First	1	30.02
	Second	2	29.32
	Third	3	28.12
	Fourth	4	28.32
1986	First	5	27.01
	Second	6	24.78
	Third	7	24.00
	Fourth	8	23.78
1987	First	9	24.25
	Second	10	23.24
	Third	11	21.98
	Fourth	12	25.00
1988	First	13	24.10
	Second	14	23.75
	Third	15	23.00

Figure 6.18 Plot of Benzene Data and Fitted Model (see Box 6.22)



6.2.4.3 Calculating the Confidence Interval for a Predicted Value

The general procedures in Section 6.1.4 can also be used to develop confidence limits for the predicted concentration at arbitrary time h (as shown in Box 6.23).

Box 6.23
Constructing Confidence Limits around an Expected Transformed Value

Referring to the fitted model (6.28), use equation (6.19) to construct confidence limits around the expected transformed value at time h:

$$U_h' = \hat{y}_h' + t_{1-\alpha/2;N-3}\, s(\hat{y}_h') \qquad (6.27)$$

and

$$L_h' = \hat{y}_h' - t_{1-\alpha/2;N-3}\, s(\hat{y}_h'). \qquad (6.28)$$

where, $\hat{y}_h' = b_0' + b_1' x_h'$; x_h = the value of the time variable at time h; and $s(\hat{y}_h')$ is the standard error of $\hat{y}_h'$ as computed from equation (6.18) using the transformed data. Note that the "t value" used in the confidence interval is based on N-3 (instead of N-2) degrees of freedom because we are estimating and additional parameter (the serial correlation) from the data.

Since the limits given in equations (6.27) and (6.28) are in the transformed scale, the upper- and lower-confidence limits in the original scale are given by:

$$y_{h,upper} = U_h' + \hat{\phi}_{obs} y_h \qquad (6.29)$$

and

$$y_{h,lower} = L_h' + \hat{\phi}_{obs} y_h. \qquad (6.30)$$

6.3 Combining Statistical Information with Other Inputs to the Decision Process

The statistical techniques presented in this chapter can be used to (1) determine whether contaminant concentrations are decreasing over time, and/or (2) predict future concentrations if present trends continue. Other factors must be used in combination with

these statistical results to decide whether the remedial effort has been successful, and when treatment should be terminated. Several factors to consider are:

- Expert knowledge of the ground water at this site and experience with other remedial efforts at similar sites;
- The results of mathematical models of ground water flow and chemistry with sensitivity analysis and assessment of the accuracy of the modeling results; and
- Cost and scheduling considerations.

The sources of information above can be used to answer the following questions:

- How long will it take for the ground water system to reach steady state before the sampling for the attainment decision can begin?
- What is the chance that the ground water concentrations will substantially exceed the cleanup standard before the ground water reaches steady state?
- What are the chances that the final assessment will conclude that the site attains the cleanup standard?
- What are the costs of (1) continuing treatment, (2) performing the assessment, and (3) planning for and initiating additional treatment if it is decided that the site does not attain the cleanup standard?

The answers to these questions should be made in consultation with both statistical and ground water experts, managers of the remediation effort and the regulatory agencies.

6.4 Summary

This chapter discussed the use of regression methods for helping to decide when to stop treatment. In particular, procedures were given for estimating the trend in contamination levels and predicting contamination levels at future points in time. General methods for fitting simple linear models and assessing the adequacy of the model were also discussed.

In deciding when to terminate treatment, the chapter emphasized that:

- Interpreting the data is usually a multiple-step process of refining the model and understanding the data;
- Models are a useful but imperfect description of the data. The usefulness of a model can be evaluated by examining how well the assumptions fit the data, including an analysis of the residuals;
- Correlation between observations collected over time can be important and must be considered in the model;
- Changes in treatment over time can result in changes in variation, and correlation and can produce anomalous behavior which must be understood to make correct conclusions from the data; and
- Consultation with a ground water expert is advisable to help interpret the results and to decide when to terminate treatment.

Deciding when to terminate treatment should be based on a combination of statistical results, expert knowledge, and policy decisions. Note that regression is only one of various statistical methods that may be used to decide when treatment should be terminated. Regression analysis was discussed in this document because of its relative simplicity and wide range of applicability; however, this does not constitute an endorsement of regression as a method of choice.

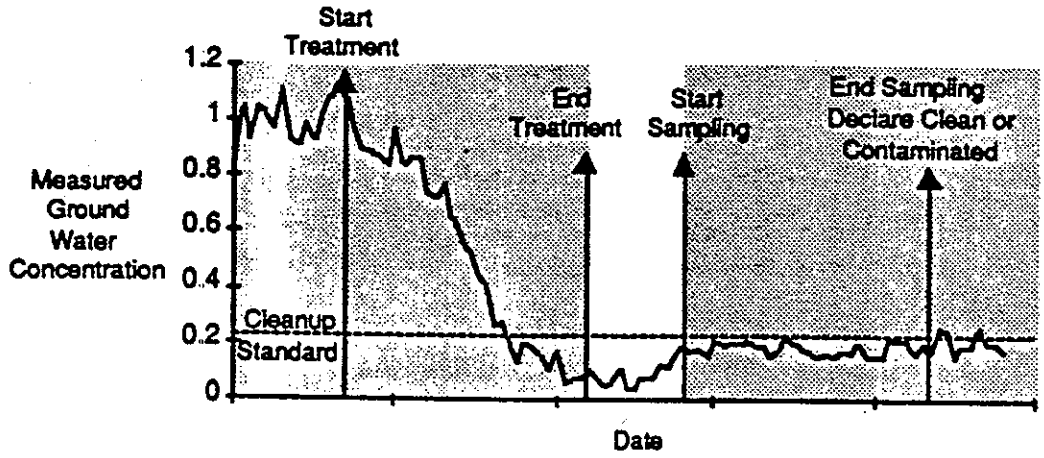
Statistical guidance for use in deciding when to begin collecting data to show that cleanup standards are met.

See Appendix 1
Section A6.1

7. ISSUES TO BE CONSIDERED BEFORE STARTING ATTAINMENT SAMPLING

After terminating treatment and before collecting water samples to assess attainment, a period of time must pass to ensure that any transient effects of treatment on the ground water system have sufficiently decayed. This period is represented by the unshaded portion in the figure below. This chapter discusses considerations for deciding when the sampling for the attainment decision can begin and provides statistical tests, which can be easily applied, to guide this decision. The decision on whether the ground water has reached steady state is based on a combination of statistical calculations, ground water modeling, and expert advice from hydrogeologists familiar with the site.

Figure 7.1 Example Scenario for Contaminant Measurements During Successful Remedial Action



The degree to which remediation efforts affect the ground water system at a site is difficult to determine and depends on the physical conditions of the site and the treatment technologies used. As previously discussed, the ground water can only be judged to attain the cleanup standard if both present and future contaminant concentrations are acceptable. Changes in the ground water system due to treatment will affect the contaminant concentrations in the sampling wells. For example, while remediation is in progress pumping can alter water levels, water flow, and thus the level of contamination being measured at monitoring wells. To adequately determine whether the cleanup standard has been attained, the ground water conditions for sampling must approximate the expected conditions in the

future. Consequently, it is important to establish when the residual effects of the treatment process (or any other temporary intervention) on the ground water appear to be negligible. When this point is reached, sampling to assess attainment can be started and inferences on attainment can be drawn. We will define the state of the ground water when temporary influences no longer affect it as a "steady state." "Steady state," although sometimes defined in the precise technical sense, is used here in a less formal manner as indicated in Section 7.1.

7.1 The Notion of "Steady State"

The notion of "steady state" may be characterized by the following components:

1.a. After treatment, the water levels and water flow, and the corresponding variability associated with these parameters (e.g., seasonal patterns), should be essentially the same as for those from comparable periods of time prior to the remediation effort.

or

1.b. In cases where the treatment technology has resulted in permanent changes in the ground water system, such as the placement of slurry wells, the hydrologic conditions may not return to their previous state. Nevertheless, they should achieve a state of stability which is likely to reflect future conditions expected at the site. For this steady state, the residual effects of the treatment will be small compared to seasonal changes.

2. The pollutant levels should have statistical characteristics (e.g., a mean and standard deviation) which will be similar to those of future periods.

The first component implies that it is important to establish estimates of the ground water levels and flows prior to remediation or to predictively model the effect of structures or other features which may have permanently affected the ground water. Variables such as the level of ground water should be measured at the monitoring wells for a reasonable period of time prior to remediation, so that the general behavior and characteristics of the ground water at the site are understood.

The second component is more judgmental. Projections must be made as to the future characteristics of the ground water and the source(s) of contamination, based

on available, current information. Of course, such projections cannot be made with certainty, but reasonable estimates about the likelihood of events may be established.

The importance of identifying when ground water has reached a steady state is related to the need to make inferences about the future. Conclusions drawn from tests assessing the attainment of cleanup standards assume that the current state of the ground water will persist into the future. There must be confidence that once a site is judged clean, it will remain clean. Achieving a steady state gives credence to future projections derived from current data.

7.2 Decisions to be Made in Determining When a Steady State is Reached

Immediately after remediation efforts have ended, the major concern is determining when ground water achieves steady state. In order to keep expenditures of time and money to a minimum, it is desirable to begin collecting data to assess attainment as soon as one is confident that the ground water has reached a steady state.

When sampling to determine whether the ground water system is at steady state, three decisions are possible:

- The ground water has reached steady state and sampling for assessing attainment can begin;
- The measurements of contaminant concentrations during this period indicate that the contaminant(s) are unlikely to attain the cleanup standard and further treatment must be considered; or
- More time and sampling must occur before it can be confidently assumed that the ground water has reached steady state.

Next, various criteria will be considered that can be used in determining whether a steady state has been reached.

7.3 Determining When a Steady State Has Been Achieved

In the following sections, qualitative and quantitative criteria involved in making the decision as to whether the ground water has returned to a steady state following

remediation are discussed. Some of these criteria are based on a comparison of present ground water levels with comparable levels before treatment. Others are based solely on measurements and conditions after treatment has terminated. To a certain extent, the decision as to when steady state has been reached is judgmental. It is not possible to prove that a ground water system has achieved steady state. Thus, it is important to examine data obtained from the ground water system to see if there are patterns which suggest that steady state has not been achieved. If there are no such patterns (e.g., in the water level or speed and direction of water flow), it may be reasonable to conclude that a steady state has been reached.

Any data on the behavior of the ground water prior to the undertaking of remediation may serve as a useful baseline, indicating what "steady state" for that system had been and, thus, to what it might return. However, the actions of remediation and the resulting physical changes in the area may change the characteristics of steady state. In this case, such a comparison may be less useful. When it seems clear that steady state characteristics have changed after remediation efforts, it is usually prudent to allow more time for remediation effects to decay.

Collection of data to determine whether steady state has been achieved should begin at the various monitoring wells at the site after remediation has been terminated. The variables for which data will be obtained should include measures related to the contaminant levels, the ground water levels, the speed and direction of the flow, and any other measures that will aid in determining if the ground water has returned to a steady state. The frequency of data collection will depend on the correlation among consecutively obtained values (it is desirable to have a low correlation). A period of three months between data collection activities at the wells may be appropriate if there appears to be some correlation between observations. With little or no correlation, monthly observations may prove useful. If the serial correlation seems to be high, the time interval between data collection efforts should be lengthened. With little or no information about seasonal patterns or serial correlations in the data, at least six observations per year are recommended. After several years of data collection, this number of observations will allow an assessment of seasonal patterns, trends, and serial correlation. It may be useful to consult with a statistician if there is some concern about the appropriate sampling frequency.

All data collected should be plotted over time in order to permit a visual analysis of the extent to which a steady state exists for the ground water. In Section 7.4,

the charting of data and the construction of plots are discussed. Section 7.4.3 provides illustrations of such plots and their interpretation. In Section 7.4.4, statistical tests that can be employed for identifying departures from randomness (e.g., trends) in the data are indicated. Suggestions for seasonally adjusting data prior to plotting are provided, and graphical methods are discussed.

7.3.1 Rough Adjustment of Data for Seasonal Effects

One concern in applying graphical techniques is that the data points being plotted are assumed to be independent of each other. Even if the serial correlation between observations is low, there may be a seasonal effect on the observations. For example, concentrations may be typically higher than the overall average in the spring and lower in the fall. To adjust for seasonal effects, one may subtract a measure of the "seasonal" average from each data value and then add back the overall average (Box 7.1). The addition of the overall average will bring the adjusted values back to the original levels of the variable to maintain the same reference frame as the original data.

Box 7.1
Adjusting for Seasonal Effects

Suppose we let x_{jk} be the jth individual data observation in year k, $\bar{x}_j$ be the average for period j obtained from the baseline period prior to treatment for period j, and $\bar{x}$ be the overall average for all data collected for the baseline period. For example, if six data values per year have been collected bimonthly for each of three years during the baseline period, six $\bar{x}_j$ values would be computed, each based on three data points taken from the three different years for which data were collected. The value $\bar{x}$ would be computed over all 18 data values. The adjusted jth data observation in year k, x'_{jk}, can then be computed from:

$$x'_{jk} = x_{jk} - \bar{x}_j + \bar{x} \qquad (7.1)$$

If there are missing values, calculate $\bar{x}_j$ as in Box 5.4.

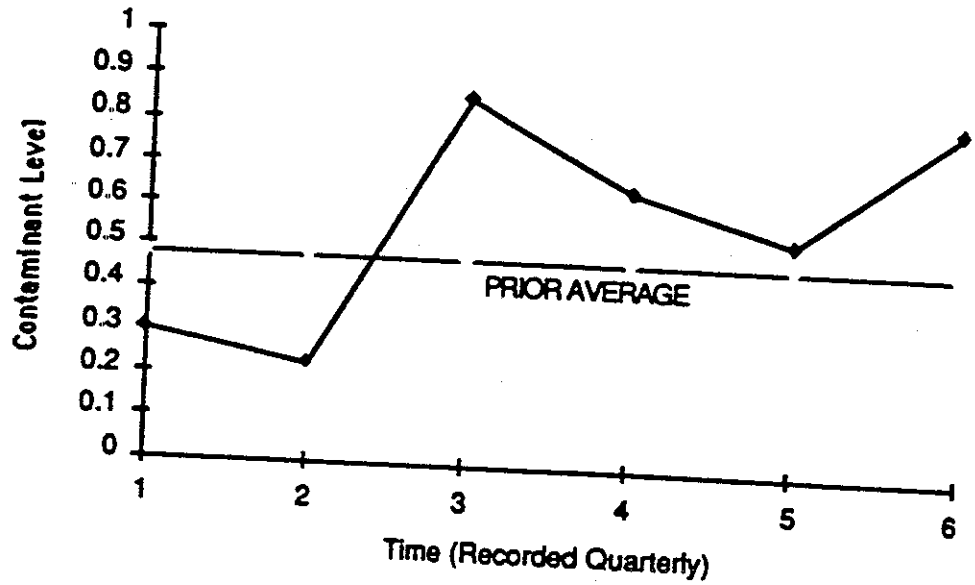
Plot the values of x_{jk} versus time. In examining these plots, checks for runs and trends can be made for the adjusted values.

7.4 Charting the Data

In general, it is useful to plot the data collected from a monitoring program. Such plots are similar to "control charts" often used to monitor industrial processes, except control limits will not appear on the charts discussed here. Use the horizontal, or X-axis, to indicate the time at which the observation was taken; and use the vertical, or Y-axis, to indicate the value of the variable of interest (e.g., the contaminant level or water table level or the value of other variables after adjustment for seasonal effects). Figure 7.2 gives an example of a plot which may be used to assess stability during the period immediately following treatment.

Notice that in Figure 7.2, the "prior average" has also been placed on the plot. This line represents the average of the baseline data collected before remediation efforts began. For example, this value could be the average of eight points collected quarterly over a two-year period. It may also be useful to plot separately the individual observations gathered to serve as the baseline data, so that information reflecting seasonal variability and the degree of serial correlation associated with the baseline period can be readily examined.

Figure 7.2 Example of Time Chart for Use in Assessing Stability



7.4.1 A Test for Change of Levels Based on Charts

If the ground water conditions after remediation are expected to be comparable to the prior conditions, we would expect that the behavior of water levels and flows to resemble that of those same variables prior to the remediation effort in terms of average and variability. One indication that a steady state may not have been reached is the presence of a string of measurements from the post treatment period which are consistently above or below the average prior to beginning remediation. A common rule of thumb used in industrial Statistical Process Control (SPC) is that if eight consecutive points are above or below the average (often called a "run" in SPC terminology), the data are likely to come from a different process than that from which the average was obtained (Grant and Leavenworth, 1980). This rule is based on the assumption that the observations are independent. This assumption is not strictly applicable in ground water studies since there is likely to be serial correlation between observations as well as seasonal variability. Assuming independent observations, an eight-point run is associated with a 1 in 128 chance of concluding that the mean of the variable of interest has changed when, in fact, there has been no change in the mean.

The above discussion suggests that for the purpose of deciding whether the ground water has achieved steady state, a string of 7 to 10 consecutive points above or below the prior average might serve as evidence indicating that the state of the ground water is different from that in the baseline period. If it is suspected that a high degree of serial correlation exists, it would be appropriate to require a larger number of consecutive points.

7.4.2 A Test for Trends Based on Charts

The charts described here provide a simple way of identifying trends. If six consecutive data points are increasing (or decreasing)[1] — sometimes stated as "5 consecutive intervals of data" so that it is understood that the first point in the string is to be counted — then there is evidence that the variable being monitored (e.g., water levels or flows, or contaminant concentrations) has changed (exhibits a trend). Again, independence

[1]This rule of 6 is based on the assumption that all 720 orderings of the points are equally likely. This is not always true. Hence such rules are to be considered only as quick but reasonable approximations.

of the observations is assumed. A group of consecutive points that increase in value is sometimes referred to as a "run up," while a group of consecutive points that decrease in value is referred to as a "run down."

With the rule of six consecutive data points described above, the chance of erroneously concluding that a trend exists is only 1 in 360, or about 0.3 percent. In contrast, a rule based on five consecutive points has a 1 in 60 chance (1.6 percent) of erroneously concluding that there is a trend, while a rule based on seven consecutive points would have a corresponding 1 in 2,520 chance (0.04 percent) of erroneously concluding that there is a trend. Thus, depending on the degree of serial correlation expected, a "trend" of 5 to 7 points may suggest that the ground water levels and flows are not at steady state.

In practice, data for many ground water samples may be collected before any significant runs are identified. For example, in a set of 30 monthly ground water flow rate measurements, there may be a run up of seven points and several shorter runs. Such patterns of runs can be analyzed by examining the length or number of runs in the series. Formal statistical procedures for analyzing trends in a time series are given by Gilbert (1987).

A quick check for a general trend over a long period of time can be accomplished as follows. Divide the total number of data points available, N, by 6. Take the closest integer smaller than N/6 and call it I. Then select the I^{th} data value over time, the $2(I^{th})$, the $3(I^{th})$, etc. For example, if N = 65, then I = 10, and we would select the 10^{th}, 20^{th}, etc., points over time. If there are six consecutive points increasing or decreasing over time, there is evidence of a trend. This test will partially compensate for serial correlation.

7.4.3 Illustrations and Interpretation

Once the plotting of data has begun, there are various patterns that may appear. Figures 7.3 through 7.8 represent six charts which indicate possible patterns that may be encountered. Evidence of departures from stability is being sought. The first five charts, except Figure 7.4, indicate evidence of instability (or in the cases of Figures 7.5 and 7.6, suspicions of possible instability), i.e., changes in characteristics over time. Figure 7.3 shows "sudden" apparent outliers or spikes that indicate unexpected variability

in the variable being monitored. Figure 7.4 illustrates a six-point trend in the variable being monitored. Figures 7.5 and 7.6 suggest that a trend may exist but there is insufficient evidence to substantiate it. Attention should be paid to the behavior of subsequent data in these cases. (In particular, the data in Figure 7.5 could indicate a general trend using the "quick check" discussed in the previous section depending on the randomly selected set of points included in the test.) Figure 7.7 reflects a change (around observation 15) in both variability (the spread of the data becomes much greater) and average (the average appears to have increased). Figure 7.8 indicates a variable that appears to be stable.

In interpreting the plots, the return to a steady state will generally be indicated by a random scattering of data points about the prior average. The existence of patterns such as runs or trends suggests instability. Patterns associated with seasonality and serial correlation should be consistent with those seen prior to remediation. At the very least, the average value for levels of contaminants after remediation should be lower than that prior to remediation. A run below the prior average for contaminant level measures would certainly not be evidence that the ground water is not at steady state, since the whole point of the remediation effort is to reduce the level of contamination. A trend downwards in contamination levels may be an indication that a steady state has not been reached. Nevertheless, if substantial evidence suggests that this decline or an eventual leveling off will be the future state of that contaminant on the site, tests for attainment of the cleanup standards would be appropriate.

On the other hand, if it seems that the average contamination level after remediation will be above the prior average or that there is a consistent trend upwards in contamination levels, it may be decided that the previous remediation efforts were not totally successful, and further remediation efforts must be undertaken. This may be done with a minimal amount of data, if, based on the data available, it appears unlikely that the cleanup standard will be met. However, what should be taken into account is the relative cost of making the wrong decision. Two costs should be weighed against each other: the cost of obtaining further observations from the monitoring wells if it turns out that the decision to resume remediation is made at a later date (the loss here is in terms of time and the cost of monitoring up to the time that remediation actually is resumed) against the cost of resuming remediation when in fact a steady state would eventually have been achieved (the loss here is in terms of the cost of unnecessary cleanup effort and time). In addition, the likelihood of making each of these wrong decisions, as estimated based on the available information, should be incorporated into the decision process.

Figure 7.3 Example of Apparent Outliers

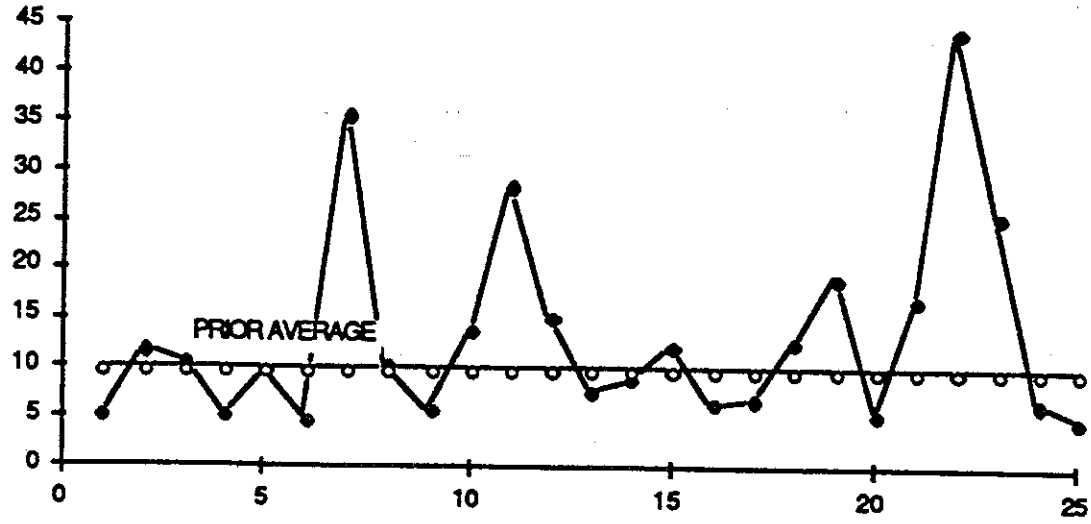


Figure 7.4 Example of a Six-point Upward Trend in the Data

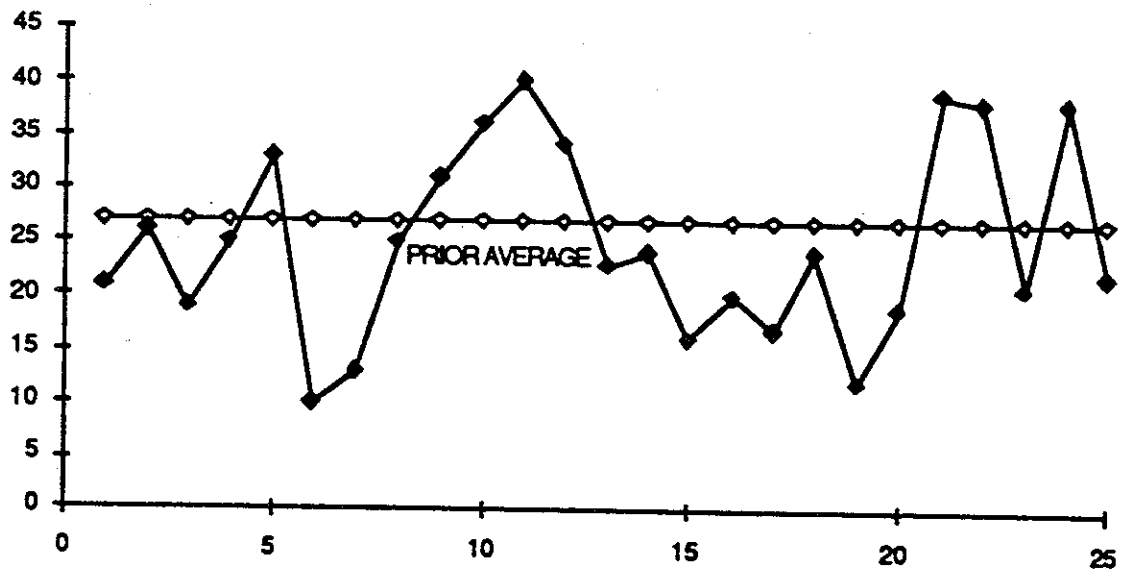


Figure 7.5 Example of a Pattern in the Data that May Indicate an Upward Trend

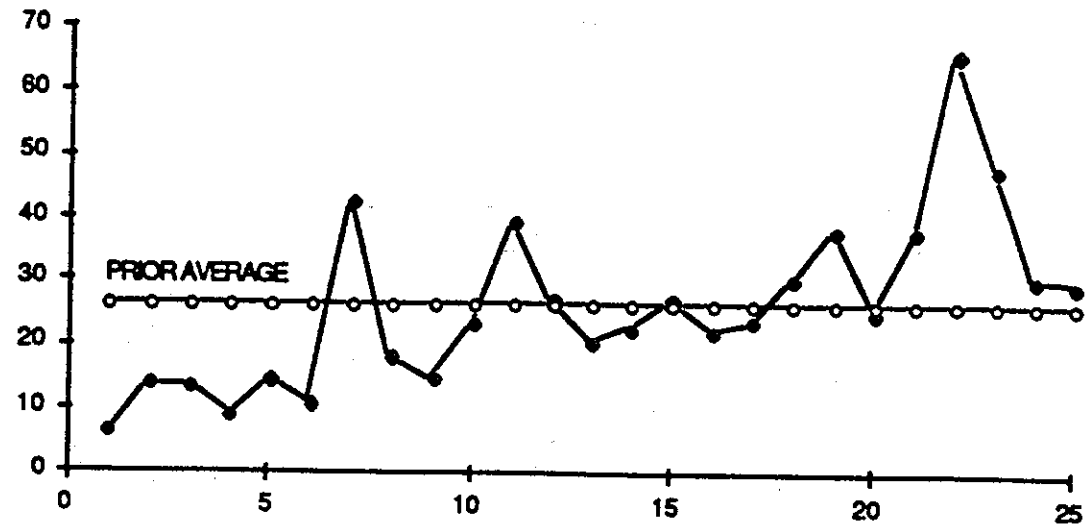


Figure 7.6 Example of a Pattern in the Data that May Indicate a Downward Trend

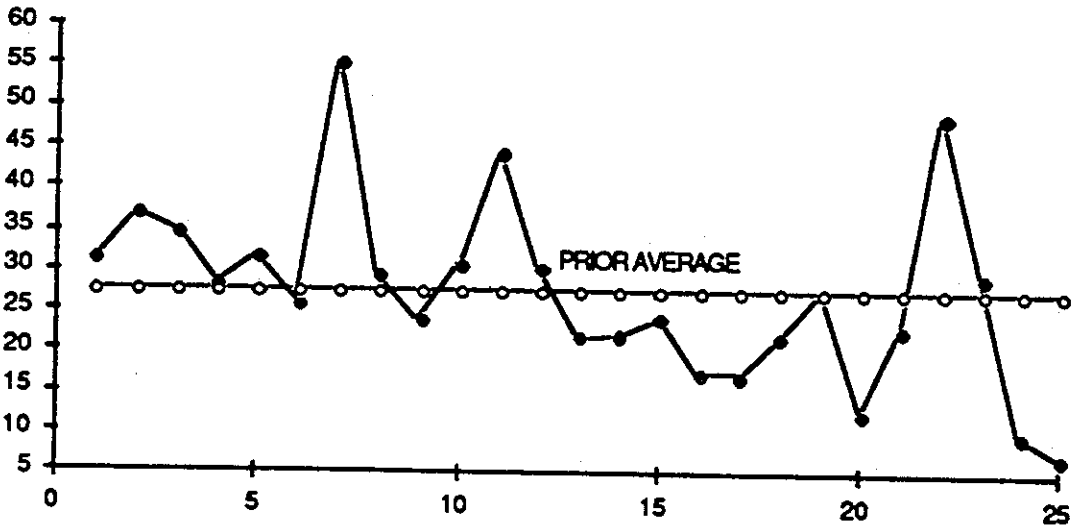


Figure 7.7 Example of Changing Variability in the Data Over Time

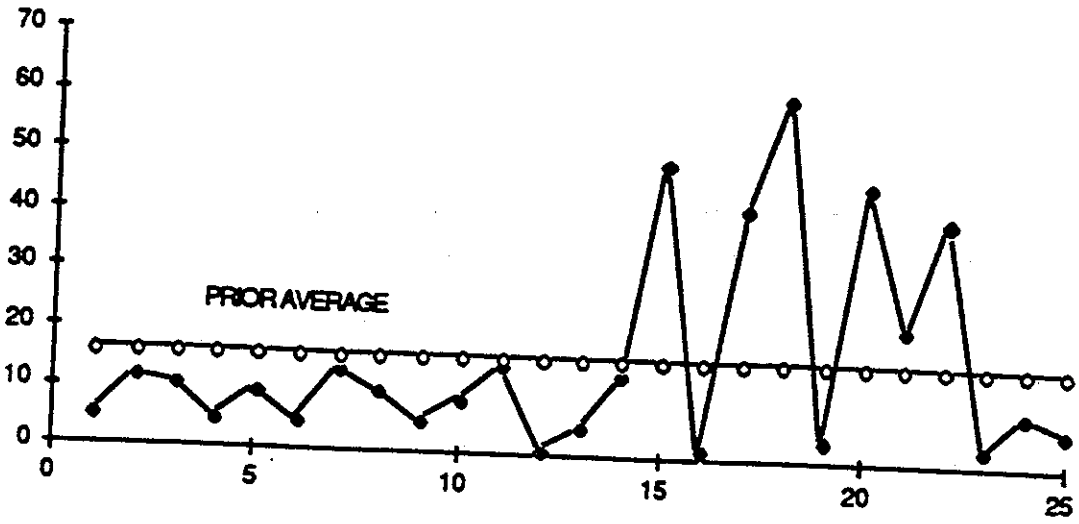
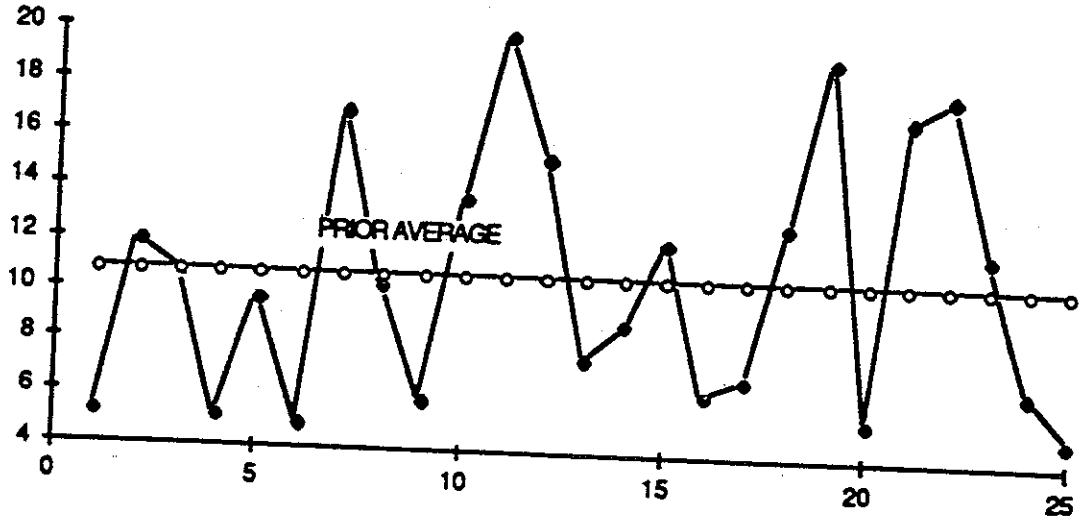


Figure 7.8 Example of a Stable Situation with Constant Average and Variation



7.4.4 Assessing Trends via Statistical Tests

The discussions in Section 7.4.3 considered graphical techniques for exploring the possible existence of trends in the data. Regression techniques discussed in Chapter 6 provide a more formal statistical procedure for considering possible trends in the data.

Other formal procedures for testing for trends also exist. Gilbert (1987) discusses several of them, such as the Seasonal Kendall Test, Sen's Test for Trend, and a Test for Global Trends (the original articles in which these tests are described were: Hirsch and Slack, 1984; Hirsch, Slack, and Smith, 1982; Farrell, 1980; and van Belle and Hughes, 1984).

The Seasonal Kendall Test provides a test for trends that removes seasonal effects. It has been shown to be applicable in cases where monthly observations have been gathered for at least three years. The degree to which critical values obtained from a normal table approximate the true critical values apparently has not been established for other time intervals of data collection--e.g., quarterly or semi-annually. This test would have to be carried out for each monitoring well separately at a site. Sen's Test for Trend is a more sensitive test for detecting monotonic trends if seasonal effects exist, but requires more complicated computations if there are missing data. The Test for Global Trends provides the capability for looking at differences between seasons and between monitoring wells, at season-well interactions, and also provides an overall trend test. All three of these tests (the Seasonal Kendall, Sen's, and the Global tests) require the assumption of independent observations. (Extensions of these tests allowing for serial correlations require that much more data be collected--for example, roughly 10 years worth of monthly data for the Seasonal Kendall test extension.) If this assumption is violated, these tests tend to indicate that a trend exists at a higher rate than specified by the chosen α level when it actually does not. Thus, these tests may provide useful tools for detecting trends, but the finding of a trend via such a test may not necessarily represent conclusive evidence that a trend exists. Gilbert provides a detailed discussion of all three tests as well as computer code that can be used for implementing the tests. However, this discussion does not consider the power of these trend tests, i.e., the likelihood that such tests identify a trend when a trend actually

exists is not addressed. If the power of these tests is low, existing trends may not be detected in a timely fashion.

7.4.5 Considering the Location of Wells

In addition to assessing the achievement of steady state in a well over time, it is also useful to consider the comparison of water and contamination levels across wells at given points in time. This can readily be done by constructing either (1) a scatter plot with water or contamination levels on the vertical axis and the various monitoring wells indicated on the horizontal axis, or (2) constructing a contour plot of concentrations or water levels across the site and surrounding area. Commercial computer programs are available for preparing contour plots. In particular, see the discussion in Volume 1 (Chapter 10) on kriging. If there are large, unexpected differences in water or contamination levels between wells, this may suggest that steady state has not yet been reached.

7.5 Summary

Finding that the ground water has returned to a steady state after terminating remediation efforts is an essential step in the establishment of a meaningful test of whether or not the cleanup standards have been attained. There are uncertainties in the process, and to some extent it is judgmental. However, if an adequate amount of data are carefully gathered prior to beginning remediation and after ceasing remediation, reasonable decisions can be made as to whether or not the ground water can be considered to have reached a state of stability.

The decision on whether the ground water has reached steady state will be based on a combination of statistical calculations, plots of data, ground water modeling, use of predictive models, and expert advice from hydrogeologists familiar with the site.

Statistical guidance for use in deciding if compliance with cleanup standards is expected to be permanent.

See Appendix 1
Section A6.2

8.6 Checking for Trends in Contaminant Levels After Attaining the Cleanup Standard

Once a fixed sample size statistical test indicates that the cleanup standard for the site has been met, there remains one final concern. The model we have used assumes that ground water at the site has reached a steady state and that there is no reason to believe that contaminant levels will rise above the cleanup standard in the future. We need to check this assumption. Regression models, as discussed in Chapter 6, can be used to do so. By establishing a simple regression model with the contaminant measure as the dependent variable and time as the independent variable, a test of significance can be made as to whether or not the estimated slope of the resulting linear model is positive (see Section 6.1.3). Scatter plots of the data will prove useful in assessing the model. When using the yearly averages, the regression can be performed without adjusting for serial correlation.

To minimize the chance of incorrectly concluding that the concentrations are increasing over time, we recommend that the alpha level for testing the slope (and selecting the t statistic in Box 6.11) be set at a small value, such as 0.01 (one percent). If, on the basis of the test, there is not significant evidence that the slope is positive, then the evidence is consistent with the preliminary conclusion that the ground water in the well(s) attains the cleanup standard. If the slope is significantly greater than zero, then the concern that contaminant levels may later exceed the cleanup standard still exists and the assumption of a steady state is called into question. In this case, further consideration must be given to the reasons for this apparent increase and, perhaps, to additional remediation efforts.

8.7 Summary

This chapter presented the procedures for assessing attainment of the cleanup standards for ground water measurements using a fixed sample size test. The testing procedures can be applied to samples from either individual wells or wells tested as a group. These procedures are used after the ground water has achieved steady state. Both parametric and nonparametric methods for evaluating attainment are discussed. If the ground water at the site is judged to attain the cleanup standards because the concentrations are not increasing and the long-term average is significantly less than the cleanup standard, follow-up monitoring is recommended to check that the steady state assumption holds.

Statistical guidance for use in developing proposals for alternative monitoring plans.

See Appendix 1
Section A7.0

8.2 Determining Sample Size and Sampling Frequency

Whether the calculation procedures used for assessing attainment use yearly averages or individual measurements, the formulas presented below for determining the required sample size use the characteristics of the individual observations. In the unlikely event that many years of observations are available for estimating the variance of yearly average, the number of years of sampling (using the same sample frequency as in the available data) can also be determined from the yearly averages using equation (5.35). The

following sections discuss the calculation of sample size for testing the mean and testing proportions.

8.2.1 Sample Size for Testing Means

The equations for determining sample size require the specification of the following quantities: Cs, μ_1, α, and β (see Sections 3.6 and 3.7) for each chemical under investigation. In addition, estimates of the serial correlation ϕ between monthly observations and the standard deviation σ of the measurements are required. For sample size determination, these quantities need not be precise. The procedures described in Section 5.10 and 5.3 may be used to obtain rough estimates of σ and the serial correlation.

The total number of samples to collect and analyze from each well is determined by selecting the frequency of sampling within a year or seasonal period and then determining the number of years or seasonal periods through which data must be collected. Given the values for Cs, μ_1, α, and β, the steps for determining sample size are provided in Box 8.1 and are discussed below in more detail.

Using previous data to estimate the serial correlation between observations separated by a month is discussed in Section 5.3. Since these estimates will not be exact, they will require the following adjustment before calculating the sample size: If the estimated correlation is less than or equal to 0.1, a serial correlation between monthly observations of 0.1 should be assumed when determining the frequency of sampling. The higher the serial correlation, the larger will be the recommended time interval between samples.

From cost records or budget projections, estimate the ratio of the annual overhead cost of maintaining sampling operations at the site to the unit cost of collecting, processing, and analyzing one ground water sample. Call this ratio $\$_R$. This ratio will be used to obtain a preliminary estimate of the sampling frequency.

Box 8.1
Steps for Determining Sample Size for Testing the Mean

(1) Determine the estimates of σ and ϕ which describe the data. Denote these estimates by $\hat{\sigma}$ and $\hat{\phi}$.

(2) Estimate the ratio of the annual overhead cost of maintaining sampling operations at the site to the unit cost of collecting, processing, and analyzing one ground water sample. Call this ratio $\$_R$.

(3) Based on the values of $\$_R$ and $\hat{\phi}$, use Appendix Table A.4 to determine the approximate number, n_p, of samples to collect per year or seasonal period. The value n_p may be modified based on site-specific considerations, as discussed in the text.

(4) The sampling frequency (i.e., the number of samples to be taken per year) is n_p or 4, whichever is larger. Denote this sampling frequency as n. Note that, under this rule, at least four samples per year per sampling well will be collected.

(5) For given values of n and $\hat{\phi}$, determine a "variance factor" from Appendix Table A.5. Denote this factor by F. For example, for $\hat{\phi} = 0.4$ and $n = 12$, the factor is $F = 5.23$.

(6) A preliminary estimate of the required number of years to sample, m_d, is

$$m_d = \frac{\hat{\sigma}^2}{F}\left\{\frac{z_{1-\beta} + z_{1-\alpha}}{Cs-\mu_1}\right\}^2 + 2 \qquad (8.1)$$

where $z_{1-\beta}$ and $z_{1-\alpha}$ are the critical values from the normal distribution with probabilities of $1-\alpha$ and $1-\beta$ (Table A.2).

(7) The number of years of data will be denoted by m and will be determined by rounding m_d to the next highest integer. The total number of samples per well will be N=nm.

Appendix Table A.4 shows the approximate number of observations per year (or period) which will result in the minimum overall cost for the assessment (see Appendix F for the basis for Table A.4). Note that the sampling frequencies given in Table A.4 are approximate and are based on numerous assumptions which may only approximate the situation and costs at a particular Superfund site. Using the table requires knowledge of the serial correlations between observations separated by one month (or one-twelfth of the

seasonal cycle) and the cost of extending the sampling period for one more year relative to taking an additional ground water sample.

Find the column in Table A.4 that is closest to the estimate of $\$_R$ being used. Find the row which most closely corresponds to ϕ. Denote the tabulated value by n_p. For example, suppose that the cost ratio is estimated to be 25 and $\phi = 0.3$. Then from Table A.4 under the fifth column (ratio = 20), $n_p = 9$. Since the costs and serial correlations will not be known exactly, the sample frequencies in Table A.4 should be considered as suggested frequencies. They should be modified to a sampling frequency which can be reasonably implemented in the field. For example, if collecting a sample every month and a half (n_p =8) will allow easy coordination of schedules, n_p can be changed from 9 to 8.

For determination of sample frequency, these quantities need not be precise. If there are several compounds to be measured in each sample, calculate the sample frequency for each compound. Use the average sample frequency for the various compounds.

It is recommended that at least four samples per year (or seasonal period) be collected to reasonably reflect the variability in the measured concentration within the year. Therefore, the sampling frequency (i.e., number of samples to be taken per year) is the maximum of four and n_p. Denote the sampling frequency by n. Note that, under this rule, at least four samples per year per sampling well will be collected.

As more observations per year are collected, the number of years of sampling required for assessing attainment can be reduced. However, there are limits to how much the sampling time can be reduced by increasing the number of observations per year. If the cost of collecting, processing, and analyzing the ground water samples is very small compared to the cost of maintaining the overall sampling effort, many samples can be collected each year and the primary cost of the assessment sampling will be associated with maintaining the assessment effort until a decision is reached. On the other hand, if the cost of each sample is very large and a monitoring effort is to be maintained at the site regardless of the attainment decision, the costs of waiting for a decision may be minimal and the sampling frequency should be specified so as to minimize the sample collection, handling, and analysis costs. It should be noted that it is assumed that the ground water remains in steady state throughout the period of data collection.

The frequency of sampling discussed in this document is the simplest and most straightforward to implement: determine a single time interval between samples and select a sample at all wells of interest after that period of time has elapsed (e.g., once every month, once every six weeks, once a quarter, etc.). However, there are other approaches to determining sampling frequency, for example, site specific data may suggest that time intervals should vary among wells or groups of wells in order to achieve approximately the same precision for each well. Considering such approaches is beyond the scope of this document, but the interested reader may reference such articles as Ward, Loftis, Nielsen, and Anderson (1979), and Sanders and Adrian (1978). It should be noted that these articles are oriented around issues related to sampling surface rather than ground water but many of the general principles apply to both. In general, consultation with a statistician is recommended when establishing sampling procedures.

Use the sample frequency per year, the estimated serial correlation between monthly observations, and Appendix Table A.5 to determine a "variance factor" for estimating the required sample size. For the given values of n and $\hat{\phi}$, determine the variance factor in Table A.5. Denote this factor by F. For example, for $\hat{\phi} = 0.4$ and n = 12, the factor is F = 5.23. For values of $\hat{\phi}$ and n not listed in Table A.5, interpolation between listed values may be used to determine F. Alternatively, if a conservative approach is desired (i.e., to take a larger sample of data), take the smaller value of F associated with listed values of $\hat{\phi}$ and n. For values outside the range of values covered in Table A.5, see Appendix F.

A preliminary estimate of the required number of years of sampling, m_d is given by equation (8.1). The first ratio in this equation is the estimated variance of the yearly average, $\hat{\sigma}^2_{\bar{x}} = \frac{\hat{\sigma}^2}{F}$. The final addition of 2 to the sample size estimate improves the estimate with small sample sizes (see Appendix F).

Because the statistical tests require a full year's worth of data, the number of years of data collection, m_d, is rounded to the next highest integer, m. Thus, n samples will be collected in each of m years, for a total number of samples per well of N where N is the product m*n. An example of using these procedures to calculate sample size for testing the mean is provided in Box 8.2.

Box 8.2
Example of Sample Size Calculations for Testing the Mean

Suppose that, for $\alpha = .01$, it is desired to detect a difference of .2 ppm from the cleanup standard of .5 ppm (for example: $Cs = .5$, $\mu_1 = .3$) with a power of .80 (i.e., $\beta = .20$). Also suppose that the ratio of annual overhead costs to per-unit sampling and analysis costs ($\$_R$) is close to 10. Further, it is estimated that $\hat{\theta} = .43$ and $\hat{\phi} = .20$. Then for $\hat{\phi} = .20$ and cost($\$_R$) = 10, Table A.4 gives $n_p = 9$. For $n_p = 9$ and $\hat{\phi} = .20$, F = 7.17 from Table A.5. Further, using equation (8.1):

$$m_d = \frac{\hat{\theta}^2}{F}\left\{\frac{z_{1-\beta} + z_{1-\alpha}}{Cs-\mu_1}\right\}^2 + 2$$

to determine the number of years, m_d, to collect data, we find

$$m_d = \frac{.43^2}{7.17}\left\{\frac{.842 + 2.326}{.5 - .3}\right\}^2 + 2 = 8.47,$$

where $z_{1-\beta} = .842$ and $z_{1-\alpha} = 2.326$, as can be found from Table A.2 or any normal probability table.

Rounding up gives a sampling duration of nine years and a total sample size of 9*9= 81 samples.

8.2.2 Sample Size for Testing Proportions

The testing of proportions is similar to the testing of means in that the average coded observation (e.g., the proportion of samples for which the cleanup standard has been exceeded) is compared to a specified proportion. The method for determining sample size described below works well when there is a low correlation between observations and no or small seasonal patterns in the data. If the correlation between monthly observations is high or there are large seasonal changes in the measurements, then consultation with a statistician is recommended. If the parameter to be tested is the proportion of contaminated samples from either one well or an array of wells, one can determine the sample size for a fixed sample size test using the procedures in Box 8.3. These procedures for determining sample size require the specification of the following quantities: α, β, P_0, and P_1 (see Section 3.7 and Section 5.4.1). In general, many samples are required for testing when testing small proportions.

Box 8.3
Determining Sample Size for Testing Proportions

(1) Compute the estimates of σ and ϕ which describe the measurements (not the coded values). Denote this estimates by $\hat{\sigma}$ and $\hat{\phi}_m$. Let $\hat{\phi} = \frac{\hat{\phi}_m}{2.5}$, ($\hat{\phi}$ is the estimated correlation between the coded observations).

(2) Estimate the ratio of the annual overhead cost of maintaining sampling operations at the site to the unit cost of collecting, processing, and analyzing one ground water sample. Call this ratio $\$_R$.

(3) Based on the values of $\$_R$ and $\hat{\phi}$, use Table A.4 to determine the approximate number, n_p, of samples to collect per year or seasonal period. Based on site-specific considerations, the value n_p may be modified to a number which is administratively convenient.

(4) The sampling frequency (i.e., the number of samples to be taken per year) is n_p or 4, whichever is larger. Denote this sampling frequency as n. Note that, under this rule, at least four samples per year per sampling well will be collected.

(5) For given values of n and $\hat{\phi}$, determine a "variance factor" from Table A.5. Denote this factor by F.

(6) For given values of F, α, β, P_0, and P_1 a preliminary estimate of the number of years to sample is

$$m_d = \frac{1}{F}\left\{\frac{z_{1-\beta}\sqrt{P_1(1-P_1)} + z_{1-\alpha}\sqrt{P_0(1-P_0)}}{P_0 - P_1}\right\}^2 \qquad (8.2)$$

where $z_{1-\beta}$ and $z_{1-\alpha}$ are critical values from the normal distribution associated with probabilities of $1-\alpha$ and $1-\beta$ (Appendix Table A.2). If m_d is less than $\frac{10}{n*P_0}$, use $m_d = \frac{10}{n*P_0}$ instead. Equation (8.2) is an adaptation of (8.1), using equation (5.25) of Chapter 5.

(7) The number of years of data will be denoted by m, and will be determined by rounding m_d to the next highest integer. The total number N of samples per well will be N=nm.

8.2.3 An Alternative Method for Determining Maximum Sampling Frequency

The maximum sampling frequency can be determined using the hydrogeologic parameters of ground water wells. The Darcy equation (Box 8.4) using the hydraulic conductivity, hydraulic gradient, and effective porosity of the aquifer, can be used to determine the horizontal component of the average linear velocity of ground water. This method is useful for determining the sampling frequency that allows sufficient time to pass between sampling events to ensure, to the greatest extent technically feasible, that there is a complete exchange of the water in the sampling well between collection of water samples. Although samples collected at the maximum sampling frequency may be independent in the physical sense, statistical independence is unlikely. Other factors such as the effect of contamination history, remediation, and seasonal influences can also result in correlations over time periods greater than that required to flush the well. As a result, we recommend that the sampling frequency be less than the maximum frequency based on Darcy's equation. Use of the maximum frequency can be approached only if estimated correlations based on ground-water samples are close to zero and the cost ratio, $\$_R$, is high. A detailed discussion of the hydrogeologic components of this procedure is beyond the scope of this document. For further information refer to Practical Guide for Ground-Water Sampling (Barcelona et al., 1985) or Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities (U.S. EPA, 1989b).

Box 8.4
Choosing a Sampling Interval Using the Darcy Equation

The sampling frequency can be based on estimates using the average linear velocity of ground water. The Darcy equation relates ground water velocity (V) to effective porosity (Ne), hydraulic gradient (i), and hydraulic conductivity (k):

$$V = \frac{(k*i)}{Ne} \qquad (8.3)$$

The values for k, i, and Ne can be determined from a well's hydrogeologic characteristics. The time required for ground water to pass through the well diameter can be determined by dividing the monitoring well diameter by the average linear velocity of ground water (V). This value represents the minimum time interval required between sampling events which might yield an independent ground water sample.