Sampling Design Guidelines
Preface

The NSW Environment Protection Authority (EPA) has prepared these guidelines to:

- encourage the use of a statistically-based approach to the design of sampling plans for contaminated sites and the interpretation of these samples for assessing and validating contaminated sites;

- provide a convenient summary of statistical methods.

The document was prepared by the EPA’s Contaminated Sites Section, Hazardous Substances Branch, to help and inform environmental consultants, local councils, and other groups interested in this area.

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Limitations

This document is not a standard statistics text and is relevant only within the context of contaminated sites.

Nor are these guidelines a stand alone document but should be used in conjunction with other relevant guidelines and information sources, such as:

- Australian and New Zealand Guidelines for the Assessment and Management of Contaminated Sites (ANZECC/NHMRC 1992),
- Guidelines for Consultant Reporting on Contaminated Sites (NSW EPA 1995),
- other relevant environmental assessment and remediation guidelines developed by the EPA, e.g. Guidelines for Assessing Service Station Sites (NSW EPA 1994).

Laboratory requirements do not form part of these guidelines, but Data Quality Objectives (DQO) should be established before sampling starts. These should include matters such as the detection limit required, the analytical procedures to be used, the level of Quality Assurance/Quality Control (QA/QC) required and the type and number of QC samples to be collected.

The guidelines do not contain occupational health and safety procedures and should therefore not be used as a field manual for soil sampling. The WorkCover Authority should be consulted regarding such requirements.

Disclaimer

The EPA has prepared this document in good faith exercising all due care and attention, however no representation or warranty, expressed or implied, is made as to the relevance, accuracy, completeness or fitness for purpose of this document in respect of any particular user's circumstances. Users of this document should satisfy themselves concerning its application to, and where necessary seek expert advice in respect of, their situation.
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1 INTRODUCTION

A major objective of investigating contaminated sites is to determine quantitatively the level of soil contamination by collecting soil samples for chemical analysis. The type of sampling program carried out and the method used to interpret the results significantly influences the validity of the assessment.

Section 5.2 of the ANZECC/NHMRC 1992 Guidelines identifies the basic sampling requirements, and this document offers additional advice on the statistical aspects of sampling by providing guidance on:

- sampling patterns and sampling depths
- the number of samples required
- the statistical interpretation of sampling results.

Specific recommendations and procedures are provided to help site investigators design statistically-based sampling strategies.

1.1 Scope

Although the guidelines were prepared for sampling soil and solid media, the statistical procedure for determining the average concentration (Procedures B and D) can also be used for sampling water.
1.2 Overview

The following table is an overview of the sampling issues contained in the guidelines.

<table>
<thead>
<tr>
<th>Sampling issue</th>
<th>The EPA's guidance</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>For site characterisation</td>
</tr>
<tr>
<td>Where to collect the samples?</td>
<td>The sampling pattern used determines where the samples will be collected. (See Section 2.3 for types of sampling pattern available.)</td>
</tr>
<tr>
<td></td>
<td>Use systematic sampling pattern. (See Section 4.1)</td>
</tr>
<tr>
<td>How many samples are required?</td>
<td>Table A provides the minimum number of sampling points required for locating hot spots. NB This is an ABSOLUTE minimum requirement.</td>
</tr>
<tr>
<td>How to evaluate the contamination status of a site?</td>
<td>The sampling results should be interpreted statistically. In general, if the results indicate a lack of hot spots and the 95% upper confidence limit (UCL) of the arithmetic average contaminant concentration of the site is below a threshold limit, e.g., the environmental investigation level of the ANZECC/NHMRC 1992 Guidelines, or other relevant health investigation level, the site can be considered uncontaminated or successfully remediated for a specific end use(s). See Procedure D for determining the 95% UCL average. Other statistical interpretations can also be applied, see Section 5.</td>
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</table>

2 DEVELOPING A STATISTICALLY BASED SAMPLING PLAN

To develop a statistically-based sampling strategy, you need to consider:

- the sampling objective
- the contaminant distribution
- the sampling pattern selection
- the sampling uncertainty.
2.1 Sampling objective

Identifying the sampling objective should always be the first step in developing a sampling plan, for it influences the sampling pattern used and the number of samples taken. Sampling is usually based on one of the following objectives:

- to gather information concerning the location, nature, level and extent of the contamination, i.e. site characterisation
- to provide statistical support for assessing the successful remediation of a site, i.e. site validation.

2.2 Contaminant distribution

The variation of contaminant concentrations over a site means that individual measurements cannot be used to fully describe the distribution of a contaminant. If the contaminant concentrations are plotted against their respective frequency of occurrence, the resulting curve (or histogram) represents the concentration distribution of that contaminant on the site. If the area under the concentration distribution curve is denoted as unity, the area under a segment of the curve can be inferred as the percentage of the site area that has contaminant concentrations within the range defined by the x-coordinates of the two ends of the curve segment. When deciding whether a site should be evaluated as 'contaminated' or 'not contaminated' by a particular contaminant, investigators should consider the percentage of the site area with contaminant concentrations less than an acceptable limit, e.g., the environmental investigation level in Table 2 of the ANZECC/NHMRC 1992 Guidelines. The higher the percentage, the more likely it is that the site is not contaminated.

Another method of describing a contaminant distribution is to determine its arithmetic average concentration—a method that requires fewer samples. It also enables investigators to make a direct comparison in terms of contaminant concentration, i.e. average contaminant concentration of the site versus an acceptable concentration limit.

The existence of hot spots is a major concern in site investigations. Hot spot detection is based on 'spatial probability' which depends on the size of the site as well as the size and shape of the target hot spot. This document does not discuss the theoretical basis of hot spot detection but provides the operational details to design a sampling program aimed at hot spot detection.
The various statistical procedures for assessing site contamination are summarised below:

- determining the percentage of site area that can be considered 'uncontaminated'
- determining the arithmetic average concentration of the contaminant
- determining if hot spots larger than a critical size exist and if so, determining their location.

Each of these methods may require totally different sample sizes, and investigators should be aware of how this can affect sampling costs. For example, sometimes 10 samples, or even less, are enough to determine whether the arithmetic average concentration is less than an acceptable limit. But at least 59 samples are required to determine whether or not 95% of the site has concentrations less than an acceptable limit. The requirements of site investigations should therefore be evaluated carefully in relation to budget constraints before committing to a specific statistical approach. Once the relevant approach is selected, the optimal number of samples required can be determined using Procedures A, B or C in this document. Failure to get the optimal number of samples will lead to either undersampling or oversampling. Undersampling can produce a statistical conclusion that a site is contaminated when in fact it is not, or vice versa. Oversampling increases sampling costs unnecessarily.

2.3 Sampling pattern selection

In a statistically-based sampling strategy samples should be collected in an unbiased manner, i.e. all locations within the sampling area should have an equal chance of being selected as a sampling point. Sampling patterns can be classified into the following four basic types.

2.3.1 Judgmental sampling pattern

For this method, sampling points are selected on the basis of the investigator's knowledge of the probable distribution of contaminants at the site. It is an efficient sampling method which makes use of the site history and field observations but has the disadvantage of being potentially biased. The quality of the sampling results depends on the experience of the investigator and the available site history information. Judgmental sampling should not be used in validation sampling.

2.3.2 Random sampling pattern

With random sampling, sampling points are selected randomly - but not arbitrarily. A legitimate 'random number generator' should be
used to determine sampling point coordinates. Most scientific calculators can generate numbers that are sufficiently 'random' for the intended purpose. The randomisation process ensures any location within the sampling area has an equal chance of being selected as a sampling point. While random sampling is statistically unbiased, sampling points, by chance, can cluster together. This makes them deficient for detecting hot spots and for giving an overall picture of the spatial distribution of the contamination. In practice, random sampling has limited use in contaminated site investigations.

2.3.3 Systematic sampling pattern

Systematic sampling, where points are selected at regular and even intervals, is statistically unbiased – providing the coordinates of the first sampling point are determined by random numbers. Systematic sampling does not generate clusters of sampling points and is easier to use to survey sampling locations than random sampling. A square grid is the commonest type of systematic sampling pattern. **NB** If the concentration levels of a contaminant are known or are suspected to exhibit periodic spatial variations, the sampling pattern should be oriented so that it will not be in or out of phase with the periodicity of the variations. Where periodic variations are known to exist but the orientation of the periodicity is not known, a 'stratified random' sampling pattern should be considered. This involves dividing the sampling area into square grids. However, instead of the usual method of collecting samples from the grid nodes, a random sample is collected within each grid, i.e. the exact sampling point within a grid is determined randomly (see 2.3.2 Random sampling pattern).

2.3.4 Stratified sampling pattern

First divide the site into sub-areas according to geological and geographical features, nature of the contamination, former usage pattern of the site, intended future use of the sub-area, and other relevant factors. Each sub-area can then be treated as an individual site and different sampling patterns and sampling densities applied. A stratified sampling pattern approach is best suited to investigations of large sites with complex contaminant distributions. This sampling pattern may require a more complex statistical analysis. It is not considered further here.
2.4 Sampling uncertainty

One can never be 'certain' about an answer derived from sampling, so the uncertainty must be specified for a statistical statement to have meaning. In statistics, uncertainty is technically referred to as confidence level or risk. Confidence level is quantified as a percentage. Risk is denoted by $\alpha$ (alpha) and has a magnitude between 0 and 1. A 95% confidence level is equivalent to a 0.05 risk. For example, if a particular statistical statement is quoted as having a 95% confidence level, or a 0.05 risk, this implies that, on average, the statistical statement will be correct 95 out of 100 times.

Unless a site investigator can demonstrate otherwise, the EPA maintains that all statistical interpretation should be carried out at a confidence level no lower than 95%.

3 SAMPLING PLANS FOR SITE CHARACTERISATION

3.1 Sampling pattern for preliminary investigations

A judgmental sampling pattern can be used where there is enough information on the probable locations of contamination. However, a systematic sampling pattern across the whole site is recommended when such information is lacking. Samples should be collected at the depth(s) where the level of contamination is expected to be most significant. The on-site investigator can determine actual sampling depth(s) based on field observations.

3.2 Sampling pattern for detailed investigations

A systematic sampling pattern is recommended when:

- the investigator has little knowledge about the probable locations of the contamination
- the distribution of the contamination is expected to be random, (e.g. landfill sites)
- the distribution of the contamination is expected to be fairly homogeneous, (e.g. agricultural lands).

a. For the purpose of this document, $\alpha$ risk is the risk of concluding that a site is 'uncontaminated' when in fact it is 'contaminated'. See Glossary for more detailed definition.
Judgmental or stratified sampling methods can be used if there is sufficient information about the probable distribution of the contamination. Judgmental sampling, however, tends to give a grossly uneven distribution of sampling points, in which case additional sampling points should be placed to provide even site coverage.

To establish the vertical extent of the contamination, samples should be collected from two or more different depths at each sampling location:

- at the surface, (i.e. between 0 and 150 mm below the surface)
- at depth or at a number of different depths.

Depth samples are usually taken in each identifiable soil horizon but if soil horizons are not evident the sample(s) should be taken at depths that determine the extent of contaminant penetration, or are relevant to the site's future use.

3.3 Minimum number of samples required

The minimum number of samples required for site characterisation depends on the complexity of the contamination, the investigator's knowledge of the site and other site-specific requirements, e.g. detecting hot spots of a particular shape and size. The actual number of samples required should be determined by the investigator on a site specific basis. When hot spots of a specific size need to be detected, the number of sampling points can be determined by Procedure A, ‘Number of sampling points required for hot spot detection’ (page 16). In the absence of site-specific requirements, Table A on the following page provides the minimum number of sampling points required for site characterisation. Table A was derived from the following principles:

- Capable of detecting a ‘reasonable’ size of hot spot in comparison to the size of the site. Reasonable size means the ‘largest area of contamination that could be dealt with if it were not identified during the investigation, but discovered only after development work on the site had started’ (BSI 1988).
- The number of samples is reasonably adequate to indicate the true value of other critical parameters of a contaminant distribution, such as the arithmetic average concentration.
TABLE A  Minimum Sampling Points Required for Site Characterisation Based on Detecting Circular Hot Spots by Using a Systematic Sampling Pattern

**Important:** The minimum sampling points listed below is not the EPA's blanket approval of minimum sampling work. Investigators must be prepared to defend the appropriateness of applying Table A only.

No guidance is provided for sites larger than five hectares. Such sites are usually sub-divided into smaller areas for more effective sampling (see section 2.3.4 Stratified sampling).

<table>
<thead>
<tr>
<th>Size of the site (hectare) 1 hectare = 10,000 m²</th>
<th>Number of sampling points recommended</th>
<th>Equivalent sampling density (points/hectare)</th>
<th>Diameter of the hot spot that can be detected with 95% confidence (metre)</th>
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<td>0.05</td>
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<tr>
<td>5.0</td>
<td>55</td>
<td>11.0</td>
<td>35.6</td>
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</table>
4 SAMPLING PLAN FOR SITE VALIDATION

4.1 Recommended sampling pattern

Systematic sampling is recommended for site validation. Random sampling can be used but, if the randomly located sampling points happen to cluster together, this method is unlikely to detect localised areas that are still contaminated. Judgmental sampling should not be used for site validation.

If a site has been remediated by excavating contaminated soil, the validation sampling should demonstrate that:

- the residual soil is uncontaminated
- the backfill material is uncontaminated.

4.1.1 Residual soil validation

The residual soil must be validated as being uncontaminated before backfilling occurs. A systematic sampling pattern, with sampling points evenly spaced across the walls and the bottom of all excavated pits, should be used. The grid spacing, which should correspond to the number of samples required, is discussed in more detail in Section 4.2. Samples should be collected at the surface of the residual layer, i.e. between 0 and 150 mm below the exposed wall surfaces and the bottom of the excavated pit.

4.1.2 Backfill material validation

The validation procedure for backfill material, which can either be imported or obtained on site, follows:

**Validation of imported backfill material**

1. The investigator should visit the source site and confirm that:
   - the site history indicates that the site is uncontaminated
   - the soil being excavated is visually clean and undisturbed (fill from the source site is not acceptable without extensive testing).

2. Take a minimum of one composite sample from the excavated soil and analyse for heavy metals, total petroleum hydrocarbons and pesticide-related organochlorine and organophosphate compounds. Confirm that their concentration levels are all below the acceptable limits.

3. If large quantities of fill are imported, regular sampling will be required. The site investigator should demonstrate that each sample measurement is either below the acceptable limits or, the
95% upper confidence limit (UCL) of the average concentration of the backfill material is below the acceptable limits. (See Procedure D for determining the 95% UCL of the average).

4. Document these steps in the validation report.

Validation of on-site backfill material

The targeted material should be stockpiled in a clean area and samples collected from the stockpile(s) using either systematic or random sampling. Site investigators must demonstrate that the backfill material meets the acceptance criteria at 95% confidence level, before backfilling.

4.2 Number of samples required

For site validation, the number of validation samples required relates to the acceptance criteria of the remediation. This in turn depends on how a contaminant distribution is to compare with an acceptable limit (see Section 2.2 Contaminant distribution). The three methods identified in Section 2.2, are:

- detecting hot spots larger than a critical size
- determining the arithmetic average concentration of the contaminant(s)
- determining the percentage of a site that is contaminated.

Given the uncertain nature of sampling (see Section 2.4), these methods can be rewritten into the following statistically-based acceptance criteria:

- Validating that a site is free of hot spots larger than a critical size, at a given confidence level
- Validating that the arithmetic average concentration of the contaminant(s) is less than an acceptable limit, at a given confidence level
- Validating that the percentage (or proportion) of the contaminated area on a site is less than a specified percentage/proportion, at a given confidence level.

Site investigators must first decide the acceptance criteria for validation. If the criteria correspond to one of those mentioned above, the optimal number of samples required can be determined using Procedures A, B or C, respectively. If multiple acceptance criteria are used, i.e. a site will be declared 'uncontaminated' or 'successfully remediated' only if several cleanup requirements are met simultaneously, the number of samples required will be the one that gives the greatest
number but not the sum of the individual numbers.

If the acceptance criteria refer to methods not mentioned above, consult a statistician to determine the optimal number of samples required.

5 INTERPRETING SAMPLING RESULTS

The statistical analysis performed should determine whether or not the acceptance criteria (see Section 4.2 and Glossary) have been met:

5.1 Determining the critical size of hot spots

If a systematic sampling pattern is used and all measurements return concentrations below an acceptable limit, the result indicates that the sampling area is free of hot spots larger than a critical size — refer Procedure F.

5.2 Determining the upper confidence limit (UCL) of the arithmetic average concentration

Procedure D contains the statistical analyses required to determine the upper-bound estimate of the arithmetic average contaminant concentration of a sampling area. For example, if 95% UCL is stated, it implies that there is a 95% probability that the 'true' (but never known) arithmetic average contaminant concentration within the sampling area will not exceed the value determined by this method. Investigators should always include the 95% UCL average concentration in their validation reports. For a site to be considered uncontaminated or successfully remediated, the typical minimum (but not necessarily the only) requirement, is that the 95% upper confidence limit of the arithmetic average concentration of the contaminant(s) is less than an acceptable limit, e.g. the environmental investigation level in ANZECC/NHMRC 1992 Guidelines.

A site or a sampling area cannot be considered uncontaminated or successfully remediated if the 95% UCL of the arithmetic average concentration exceeds the acceptable limit.

5.3 Determining the proportion of contaminated area

At a contaminated site the high side of the extreme concentrations are often a primary concern. In some circumstances, a site can only be considered uncontaminated or successfully remediated if, in
addition to meeting the 95% UCL average concentration requirement (Section 5.2), you can ensure that only a certain proportion of an area or a stockpile of soil has concentrations exceeding an acceptable limit – refer Procedure E.

6 THE USE OF COMPOSITE SAMPLING

Composite sampling is often used to reduce the cost of chemical analyses (SAHC 1995). Individual samples collected as far apart as 20 metres, are bulked and thoroughly mixed together to form a single composite sample for chemical analyses. In principle, the concentration of the composite sample represents the average concentration of the sub-samples. However, a major drawback of compositing is that a sub-sample containing a high concentration of contaminant can remain undetected because its concentration was diluted in the compositing process. If that sub-sample actually represents a hot spot, it will not be identified. The problem of hot spot dilution can be resolved by using one of the methods described below:

Method (1) Divide the acceptable limit against which the sample results are to be compared by \( n \), where \( n \) is the number of sub-samples making up the composite. This is based on the worst-case scenario that one sub-sample has a high concentration while the remaining sub-samples all have zero concentration. If a composite sample fails to meet the adjusted acceptable limit, all sub-samples of the failed composite will be analysed individually. This conservative approach can lead to many re-analyses of the sub-samples which erodes the cost advantage of composite sampling.

Method (2) The site investigator provides evidence – a thorough site history review, a statistical analysis of the previous sampling results, demonstrating the degree of mixing of the soil during the remediation, etc. – that the possibility of the site containing a hot spot larger than a critical size is minimal. If it can be demonstrated that a hot spot should not exist, an adjustment to the acceptable limit is not required.

Method (3) Similar to Method (1) but assigning a non-zero concentration value to the sub-samples, e.g. the background concentration of the contaminant. The adjusted acceptable limit will become more realistic, thus reducing frequent re-analyses of the sub-samples. Whenever this method is chosen the concentration value assigned is judgmental: it should only be considered on a case-by-case basis, and be fully justified.
6.1 Rules to observe

Composite sampling must comply with the following rules. Violation of these rules could invalidate the sampling results.

**Analytes**

- Composites are satisfactory for inorganic substances, e.g. heavy metals, or substances of low volatility
- Volatile substances including Total Petroleum Hydrocarbons are not suitable for composite sampling.

**Soil/fill type**

- Samples to be composited must be collected from the same soil/fill horizon
- Soil with high clay content is not suitable for composite sampling because of the difficulty of mixing the sub-samples thoroughly.

**Method of compositing**

Sub-samples should be:

- equal in size
- from immediately adjacent sampling points
- evenly spaced
- composited laterally.

No more than 4 sub-samples should be included in a composite sample.
GLOSSARY

The following definitions relate only to this document.

Acceptable limit A threshold concentration value below which the level of contamination is regarded as acceptable. An acceptable limit can either be adopted from the appropriate guidelines, e.g. Table 1 and Table 2 of the ANZECC/NHMRC 1992 Guidelines, or it can be derived on a site specific basis using risk assessment. Where site remediation is involved, acceptable limits are often referred to as ‘cleanup standards’ or ‘remediation standards’.

Acceptance criteria A statistical statement specifying how a contaminant distribution will be compared with an acceptable limit (see above definition) to determine whether a site should be evaluated as ‘contaminated’ or ‘uncontaminated’. The concentrations of a contaminant can vary over orders of magnitude in a sampling area. The arithmetic average concentration of a distribution can be very different from the concentration of, say, the 95th percentile of the same distribution. All site assessments must state the appropriate acceptance criteria as well as the appropriate acceptable limits.

Coefficient of variation (CV) The standard deviation of a distribution divided by the mean of the distribution. CV is the measurement of the relative homogeneity of a distribution. Low CV values, e.g., 0.5 or less, indicate fairly homogeneous contaminant distribution. CV’s with values over 1 imply that the concentration distribution of a contaminant is heterogeneous and probably highly skewed to the right.

Composite sample The bulking and thorough mixing of soil samples collected from more than one sampling location to form a single soil sample for chemical analyses.

Confidence level The probability, expressed as a percentage, that a statistical statement is correct. Confidence level is the opposite expression of ‘risk’ (see definitions of $\alpha$ and $\beta$ risks). For the purpose of this document in which $\alpha$ risk is the risk that needs to be regulated, the confidence level is always equal to $1 - \alpha$.

Contaminated For the purpose of this document and depending on the context, ‘contaminated’ can have slightly different meanings. If a site or a sampling area is evaluated as ‘contaminated’, it means that the site or the sampling area as a whole has not met the acceptance criteria (see definition of acceptance criteria). 'Contaminated' can also be used to describe a localised area or soil that has contaminant concentrations exceeding an acceptable limit (see definition of accept-
able limit). **NB** Depending on what the acceptance criteria are, an entire site could be considered 'uncontaminated' even though a certain percentage of the site is expected to be 'contaminated'.

**Grab samples** Samples collected from different locations that will not be composited but analysed individually.

**Hot spot** A hot spot is defined as a localised area where the level of contamination within that area is noticeably greater than that in surrounding areas. **NB** This definition defines hot spot only as relatively high in contamination.

**Residual soil** Soil remaining after the contaminated soil has been removed.

**Sample size** The number of samples or sampling points selected in a sampling program.

**Sampling pattern** The locational pattern of sampling points within a sampling area.

**Sampling point** The lateral location at which a soil sample is collected.

**Site characterisation** The assessment of the nature, level and extent of contamination. A typical site characterisation involves a preliminary investigation followed by a detailed investigation where warranted.

**Site validation** The process of showing that a site is successfully remediated.

**Sub-sample** A sample that will be bulked together with other sub-samples to form a composite for chemical analyses.

**α risk** The probability, expressed as a decimal, of making a 'type I error' when the hypothesis is tested statistically. A type I error **wrongly rejects** a null hypothesis when in fact the null hypothesis is true. In this document, the null hypothesis always assumes that the site is 'contaminated' and thus the α risk refers to the probability of a site being validated 'uncontaminated' when in fact it is 'contaminated'.

**β risk** The probability, expressed as a decimal, of making a 'type II error' when a hypothesis is tested statistically. A type II error **wrongly accepts** a null hypothesis when in fact the null hypothesis is false. In this document, the null hypothesis always assumes that the site is 'contaminated' and thus the β risk refers to the probability that a site is concluded 'contaminated' when in fact the site is 'uncontaminated'.
Procedure A. Number of sampling points required for hot spot detection


This method is based on detecting circular hot spots with 95% confidence using a square grid sampling pattern. To detect hot spots of other shapes, at other confidence levels or by using other sampling patterns, consult the following reference materials:


(2) Ferguson C.C., The statistical basis for spatial sampling of contaminated land, Ground Engineering, June 1992, pp34–38.

Equations used:

\[ G = \frac{R}{0.59^b} \quad (1) \]

\[ n = \frac{A}{G^2} \quad (2) \]

Where

\( n \) = Number of sampling points needed

\( A \) = Size of the sampling area, in metre²

\( G \) = Distance between two sampling points, i.e., the grid size of the sampling pattern, in metres

\( R \) = Radius of the smallest hot spot that the sampling intends to detect, in metres.

Procedure

1. Determine the radius of the hot spot, \( R \), that needs to be detected.

2. Calculate the grid size, \( G \), from Equation (1).

3. Determine the number of sampling points required, \( n \), from Equation (2).

b. This is based on \( \beta = 0.05 \) and \( S = 1.0 \), see Figure 10.3 of Gilbert (1987).
WORKED EXAMPLE A

An investigator wants to determine if a 0.2 hectare site contains hot spot(s) larger than 10 metres in diameter. How many sampling points will be required and what grid size should it be?

Solution

The radius of the target hot spot, \( R = 10/2 \) metres = 5 metres

From Equation (1),

\[ G = \frac{5}{0.59} = 8.5 \text{ metres} \]

From Equation (2),

\[ n = \frac{A}{G^2} = \frac{2000}{(8.5)^2} = 28 \]

The number of sampling points in a plane is approximately 28 and the grid size of the sampling pattern is 8.5 metres, i.e. the sampling points should be 8.5 metres apart.
Procedure B. Number of samples required for determining the average concentration


This method determines the number of samples needed if the objective of the sampling is to show that the average concentration of a contaminant is below an acceptable limit. The method can be applied to sampling an area or to sampling a stockpile(s) of soil.

The method requires that the probable average concentration and standard deviation of the contaminant are known. This method is most applicable for validation sampling, where the average concentration and the standard deviation can be estimated from the previous sampling results.

Equation used

\[ n = \frac{6.2 \cdot \sigma^2}{(C_s - \mu)^2} \]  \hspace{1cm} (3)

Where

\[ n = \text{Number of samples needed} \]
\[ \sigma = \text{Estimated standard deviation of contaminant concentrations in the sampling area, mg/kg} \]
\[ \mu = \text{Estimated average concentration in the sampling area, mg/kg} \]
\[ C_s = \text{Acceptable limit, in mg/kg} \]

c. Based on 0.05 \( \alpha \) risk and 0.2 \( \beta \) risk. See Glossary for definitions of \( \alpha \) risk and \( \beta \) risk.
Procedure

1. Estimate \( \mu \) based on previous sampling results or by judgment. \( \mu \) should have a value less than \( C_r \).

2. Estimate \( \sigma \) based on previous sampling results. Where no previous sampling result is available, a crude estimate of \( \sigma \) can be obtained by using the following method:
   
   (i) Estimate the lowest possible concentration, \( C_L \), in the sampling area.
   
   (ii) Estimate the highest possible concentration, \( C_H \), in the sampling area.
   
   (iii) Estimate \( \sigma \) using the following equation:

   \[
   \sigma = \frac{C_H - C_L}{6} \quad (4)
   \]

3. Determine what the acceptable limit should be.

4. Compute \( n \) using Equation (3).

WORKED EXAMPLE B

A site is to be validated. Judging from the previous sampling results, the investigator expects that the average concentration of a particular contaminant on the site will be around 100 mg/kg. The acceptable limit is 150 mg/kg. Previous sampling indicates that the maximum and minimum concentrations are 450 mg/kg and 30 mg/kg, respectively. How many samples should be taken for validation?

Solution

From Equation (4)

\[
\sigma = \frac{450 - 30}{6} = 70 \text{ mg/kg}
\]

From Equation (3)

\[
n = \frac{6.2(70)^2}{(150 - 100)^2} = 13
\]

The number of samples needed is 13.
**Procedure C.** Number of samples required for determining the proportion of contamination


This method determines the number of samples needed if the objective of sampling is to show that:

(i) a site has no greater than a certain proportion of its area where concentrations exceed an acceptable limit

(ii) a stockpile(s) of soil has no greater than a certain proportion of its volume where concentrations exceed an acceptable limit.

**Equation used**

\[
 n = \left[ \frac{1.65 \sqrt{P_0(1-P_0)} - 0.84 \sqrt{P_1(1-P_1)}}{P_0 - P_1} \right]^2
\]  

(5)

Where

- \( n \) = Number of samples needed
- \( P_0 \) = Maximum allowable proportion of an area or a stockpile of soil that has concentrations exceeding an acceptable limit.
- \( P_1 \) = Expected proportion of an area or a stockpile of soil that has concentrations exceeding an acceptable limit.

**Procedure**

1. Determine \( P_0 \). The value of \( P_0 \) typically ranges from 0.05 (testing 95% of an area or a stockpile of soil is below an acceptable limit) to 0.25 (testing 75% of an area or a stockpile of soil is below an acceptable limit).

2. Determine \( P_1 \). \( P_1 \) must have a value less than \( P_0 \).

3. Calculate \( n \) from Equation (5).

---

d. The equation is based on 0.05 \( \alpha \) risk and 0.2 \( \beta \) risk.
WORKED EXAMPLE C

A site has been remediated and requires validation. The remedial action plan states that the site will be declared clean only if at least 75% of its area has concentrations less than the cleanup standard. Judging from experience, the investigator believes that at least 90% of the site should be clean. How many samples should the investigator take to show that the cleanup requirement has been attained?

Solution

From Equation (5)

\[ P_0 = 1 - 0.75 = 0.25 \]
\[ P_1 = 1 - 0.90 = 0.10 \]

\[ n = \left[ (1.65)[0.25(1 - 0.25)]^{1/2} + (0.84)[0.10(1 - 0.10)]^{1/2} \right]^2 \]
\[ + [0.25 - 0.10]^2 = 42 \]

The number of samples needed is 42.
Procedure D. Determining the 95% upper confidence limit (UCL) of the arithmetic average concentration

This method can be applied to many forms of contaminant concentration distributions including those that are not normally distributed. This is based on the Central Limit Theorem which states that sample means tend to exhibit a normal distribution even though the mother population is not normally distributed. However, if the coefficient of variation is greater than 1.2 and statistical tests support the hypothesis of a lognormal distribution, use Procedure G to determine the upper confidence limit of the average concentration.

Equation used

\[
\text{UCL average} = \bar{x} - t_{\alpha, n-1} \frac{s}{\sqrt{n}} \quad (6)
\]

Where

\text{UCL average} = \text{Upper confidence limit of the arithmetic average concentration of the sampling area at the 1-\alpha confidence level.}

\text{\(\alpha\) = The probability that the 'true' average concentration of the sampling area might exceed the UCL average determined by Equation 6. For more detailed definition of \(\alpha\) risk, see Glossary.}

\text{n = Number of sample measurements.}

\text{\(\bar{x}\) = Arithmetic average of all sample measurements}

\text{t_{\alpha, n-1} = A test statistic (Student's t at an \(\alpha\) level of significance and \(n - 1\) degrees of freedom)}

\text{s = Standard deviation of the sample measurements}

Procedure

1. Determine the confidence level, for 95% confidence level, \(\alpha = 0.05\). Obtain the corresponding value of \(t_{\alpha, n-1}\) from Table B.

2. Compute the 95% UCL average from Equation (6).

\[\text{e. Refer Gilbert R.O., Statistical Methods for Environmental Pollution Monitoring,}
\text{Chapter 13, page 164, Van Nostrand Reinhold, 1987}\]
TABLE B  Values of Student’s t at selected α and degrees of freedom (df)

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</table>

For the purpose of this document, df = n – 1, where n is the number of sample measurements.
WORKED EXAMPLE D

A site has been remediated. The remedial action plan states that the site will be declared clean only if the 95% UCL of the average concentration of a contaminant is less than 50 mg/kg. 20 validation samples were collected from the site using systematic sampling. The contaminant concentrations are shown below (in mg/kg):
8, 20, 25, 30, 15, 24, 30, 38, 43, 48, 55, 40, 41, 46, 52, 55, 62, 65, 70, 80

Has the site met the cleanup requirement?

Solution

(i) Determine the coefficient of variation (CV) of the sample measurements:

\[ \bar{x} = 42.4 \text{ mg/kg, } s = 19.1 \text{ mg/kg} \]
\[ \text{CV} = \frac{19.1}{42.4} = 0.45 < 1.2 \]

The low value of CV implies that Procedure D is applicable for determining the average concentration of the site.

(ii) Determine the value of \( t \):

For 95% confidence, \( \alpha = 0.05 \)

From Table B, \( t_{0.05.19} = 1.729 \)

(iii) Determine the 95% UCL average:

From Equation (6)

95% UCL average = \( 42.4 + (1.729)(19.1) / \sqrt{20} \)
= \( 42.4 + 7.38 = 49.8 \text{ mg/kg, which is less than 50 mg/kg.} \)

The statistical analysis indicates that there is a 95% probability that the arithmetic average concentration of the contaminant will not exceed 49.8 mg/kg. The cleanup requirement, therefore, has been met.
Procedure E. Determining proportion of contaminated area

Reference for Method A:


Reference for Method B:


Method A and Method B are based on a non-parametric statistical approach and therefore are applicable to any type of distribution.

The method starts by comparing the sample measurements with an acceptable limit. Measurements exceeding the limit are recorded. If the number that exceed the limit, and the total number of sample measurements are known, the proportion of the site with contaminant concentrations exceeding the acceptable limit can be determined statistically.

An equation is not required, as all statistical data have been converted into tables for ease of use. See Table C.

Two methods are presented. If the proportion of the contaminated area is expected to be equal to or smaller than 0.1, use Method A. If the proportion of the contaminated area is expected to be larger than 0.1, use Method B.

Method A

A1 Determine the acceptable limit.

A2 Determine the total number of sample measurements

A3 Determine the number of sample measurements, Y, that have concentrations exceeding the acceptable limit. If Y > 10, go to Method B.

A4 Go to Table C.

A5 Table C provides 95% confidence level (part A of the table) and 90% confidence level (part B of the table). Go to the appropriate sub-table (i.e., part A or part B).

A6 The table's extreme left column lists the Y values from 1 to 10. Read across the row that has the Y value equal to Step A3. Stop at the column where the number equals to or becomes less than the total number of sample measurements determined in step A2. Read up the column. The decimal value appearing on the top of the table is the answer – the upper-bound measurement of the proportion of the site that is contaminated, at the specified confi-
dence level. The 100 times of the decimal value gives the answer in terms of percentage.

If all numbers appearing on the row are greater than the total number of sample measurements determined in Step A2, this indicates that the proportion of the contaminated area is greater than 0.1. Method A is no longer applicable. Use Method B.

**Method B**

B1 Determine the acceptable limit.

B2 Determine the total number of sample measurements, n, and the number of samples that exceed the acceptable limit, Y.

B3 Compute the value of Y/n.

B4 Go to Table C, Method B.

B5 Go to the appropriate n and Y/n values, the table will provide the upper-bound estimate of the proportion of contaminated area at 95% (two-sided) confidence level. Interpolate for the intermediate n and Y/n values.
### TABLE C  Work tables for Procedure E

**METHOD A**

See Method A in Procedure E for the use of the following tables.

\[ Y = \text{Number of sample measurements that have concentrations exceeding the acceptable limit} \]

#### Part A—Proportion of contamination at 95% confidence level

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<th>( 0.03 )</th>
<th>( 0.04 )</th>
<th>( 0.05 )</th>
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#### Part B—Proportion of contamination at 90% confidence level

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</table>

Source: These tables have been taken from Table A.10, USEPA (1989)
METHOD B

See Method B in Procedure E for the use of the following tables.

\[ Y = \text{Number of sample measurements that have concentrations exceeding the acceptable limit} \]

\[ n = \text{Total number of sample measurements} \]

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<td>0.45</td>
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</table>

Source: These tables have been taken from Table A4, Conover (1980)

\[ f \text{ Two sided, i.e., } 1 - 2\alpha = 0.95 \]

28
WORKED EXAMPLE E

As part of the site validation, 60 samples were collected from a site using a systematic sampling pattern. The chemical analyses of the samples indicated that four samples had contaminant concentrations exceeding the acceptable limit.

What proportion of the remediated area is contaminated at 95% confidence level?

Solution

Use Method A:
For Y = 4, the smallest number on the row in Table C, Part A, is 89, which is larger than 60. This indicates that the proportion of the contaminated area is greater than 0.1 at 95% confidence. Method A is not applicable.

Use Method B:
Y = 4 and n = 60
Y/n = 4/60 = 0.067
Y/n = 0.067 is not provided in Table D. Interpolation is required between Y/n = 0.06 and Y/n = 0.08.

The proportion of contaminated area is 0.15 for Y/n = 0.06 and 0.18 for Y/n = 0.08. Interpolating between these two values gives the proportion of contaminated area = 0.16 for Y/n = 0.067.

The proportion of contaminated area should be no greater than 0.16 at 95% (two-sided) confidence level.
Procedure F. Determining the critical size of hot spots


If a systematic sampling pattern is used and all sample measurements return concentrations below an acceptable limit, the result can be interpreted as indicating that the sampling area is free of hot spots larger than a critical size. This method determines what this critical size is.

Equation used

\[ L = K \times G \quad (7) \]

Where

- **L** = Radius of a circular hot spot, in metres. If the hot spot is expected to be elliptical, L is one half the length of its major axis.
- **K** = A statistical constant. Its value is dependent on the expected shape of the hot spot and the confidence level required for the sampling.
- **G** = Distance between two sampling points, i.e., the grid size of the sampling pattern, in metres.

Procedure

1. Choose the appropriate K value from Table D.
2. Identify the grid size of the sampling.
3. Determine the critical size of the hot spot from Equation (7).

WORKED EXAMPLE F

A site has been sampled by using a 20 metre square grid pattern. None of the sample measurements have contaminant concentrations higher than the acceptable limit. What is the smallest hot spot that the investigator can declare the site free of?

Solution

Assuming a circular hot spot at 95% confidence level

- **K** = 0.59 and **G** = 20 metres

From Equation (7)

\[ L = K \times G = 0.59 \times 20 = 11.8 \text{ metres} \]

Diameter of the hot spot = \(11.8 \times 2 = 23.6\) metres
The investigator can declare that the site should be free of circular hot spots larger than 24 metres in diameter.

Assuming an elliptical hot spot at 95% confidence level

\[ K = 0.90 \text{ and } G = 20 \text{ metres} \]

From Equation (7)

\[ L = K \times G = 0.90 \times 20 = 18 \text{ metres} \]

The investigator can declare that the site should be free of elliptical hot spots larger than 36 metres for the major axis and 18 metres for the minor axis.

**TABLE D**  
K values for hot spot detection based on a square grid sampling pattern

<table>
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<th>Confidence level (%)</th>
<th>Circular hot spot</th>
<th>Elliptical hot spot (aspect ratio 2:1)</th>
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</table>

Source: This table has been taken from Figure 10.3 of Gilbert (1987)
Procedure G. Determining the 95% UCL of the average concentration for a lognormal distribution


Equation used

\[
\text{UCL average} = \exp \left( \bar{y} + 0.5s_{\bar{y}}^2 - \frac{s_{\bar{y}}}{{n}^{1/2}}H \right) \quad (8)
\]

Where

- \( \text{UCL average} \) = Upper limit of the average concentration at 95% confidence level
- \( \bar{y} \) = Arithmetic average of the log-transformed sample measurements
- \( s_{\bar{y}}^2 \) = Variance of the log-transformed sample measurements
- \( n \) = Number of sample measurements
- \( H \) = A statistical constant. Its value is dependent on the values of \( s_{\bar{y}} \) and \( n \).
- \( \exp \) = Exponential function, i.e., 2.7183 to the power of the value inside the brackets.

**Procedure**

1. Logarithmically transform the sample measurements. Let \( y_i = \ln x_i \), where \( x_i \) is the original individual sample measurement.
2. Compute \( \bar{y} \).
   \[
   \bar{y} = \frac{\Sigma y_i}{n}
   \]
3. Compute \( s_{\bar{y}}^2 \) and \( s_{\bar{y}} \).
   \[
   s_{\bar{y}}^2 = \frac{\Sigma (y_i - \bar{y})^2}{(n - 1)}
   \]
   \[
   s_{\bar{y}} = \sqrt{s_{\bar{y}}^2}
   \]
4. Determine the value of \( H \) from Table E on the following page. For values of \( s_{\bar{y}} \) and \( n \) that are not listed in the table, use interpolation.
5. Compute the UCL average from Equation (8).
### TABLE E  Values of H for computing 95% UCL on a lognormal mean

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<td>6.00</td>
<td>78.47</td>
<td>27.81</td>
<td>19.68</td>
<td>15.45</td>
<td>14.08</td>
<td>12.81</td>
<td>11.44</td>
<td>10.36</td>
<td>9.449</td>
<td>8.661</td>
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<tr>
<td>7.00</td>
<td>91.55</td>
<td>32.43</td>
<td>22.94</td>
<td>18.00</td>
<td>16.39</td>
<td>14.90</td>
<td>13.31</td>
<td>12.05</td>
<td>10.98</td>
<td>10.05</td>
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<tr>
<td>8.00</td>
<td>104.6</td>
<td>37.06</td>
<td>26.20</td>
<td>20.55</td>
<td>18.71</td>
<td>17.01</td>
<td>15.18</td>
<td>13.74</td>
<td>12.51</td>
<td>11.45</td>
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<tr>
<td>9.00</td>
<td>117.7</td>
<td>41.68</td>
<td>29.46</td>
<td>23.10</td>
<td>21.03</td>
<td>19.11</td>
<td>17.05</td>
<td>15.43</td>
<td>14.05</td>
<td>12.85</td>
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<tr>
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<td>130.8</td>
<td>46.31</td>
<td>32.73</td>
<td>25.66</td>
<td>23.35</td>
<td>21.22</td>
<td>18.93</td>
<td>17.13</td>
<td>15.59</td>
<td>14.26</td>
</tr>
</tbody>
</table>

Source: This table has been taken from Table A12, Gilbert (1987)

### WORKED EXAMPLE G

Ten soil samples were taken randomly from a site and analysed chemically for a particular contaminant with the following results (in mg/kg):

350, 160, 90, 75, 48, 34, 28, 22, 18, 8

What is the average concentration of the contaminant on the site?
Solution

The probability plot of the sample measurements clearly indicates that the distribution is lognormal. The coefficient of variation of the data set also exceeds 1.2, therefore the equation given in Procedure G should be used.

Determine $\bar{y}, S_y^2$ and $S_y$

<table>
<thead>
<tr>
<th>x</th>
<th>$\bar{y} = \ln x$</th>
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<tbody>
<tr>
<td>350</td>
<td>5.858</td>
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<tr>
<td>160</td>
<td>5.075</td>
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<tr>
<td>90</td>
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<td>34</td>
<td>3.526</td>
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<td>28</td>
<td>3.332</td>
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<td>22</td>
<td>3.091</td>
</tr>
<tr>
<td>18</td>
<td>2.890</td>
</tr>
<tr>
<td>8</td>
<td>2.079</td>
</tr>
</tbody>
</table>

$\bar{y} = 3.854, S_y^2 = 1.242, S_y = 1.115$

Determine H

From Table D, for $n = 10$ and $S_y = 1.115$, $H$ should be between 3.103 (for $S_y = 1.00$) and 3.639 (for $S_y = 1.25$). Using interpolation, $H = 3.350$.

Determine the 95% UCL average

From Equation (8)

\[
UCL \text{ average} = \exp \left[ 3.845 + (0.5)(1.242) + (1.115)(3.35)/\sqrt{(10 - 1)} \right] = \exp (4.466 + 1.245) = \exp (5.711) = 302 \text{ mg/kg}
\]

The concentrations distribution of the contaminant resembles a lognormal distribution. There is a 95% probability that the average concentration of the contaminant on the site will not exceed 302 mg/kg. It should be noted that the sample mean is $\exp (4.466) = 87$ mg/kg while the 95% UCL of the mean is 302 mg/kg. This indicates that analysing more samples is likely to significantly reduce the 95% UCL of the mean.
REFERENCES


EPA (Environment Protection Authority NSW) 1994 Guidelines for Assessing Service Station Sites Sydney.


